Solar Irradiance and Photovoltaic Measurements

From Solar Radiation to PV Arrays

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Overview of talk

- Overview of existing Solar and PV standards (Sept 2011)
- Solar radiation instruments and characteristics
- Setting up a monitoring system for solar radiation measurements
- Calculation procedures for Global irradiance
- PV Cell and Module measurements (indoor/outdoor)
- PV array measurements and extrapolation to STC
- Traceability (irradiance) and uncertainty issues

Standards - 1

- ISO Standards
  - ISO 9845 — Reference solar spectral irradiance at the ground at different receiving conditions – Part1: Direct normal and hemispherical solar irradiance for air mass 1.5
  - ISO 9846 (1993-13) — Calibration of a pyranometer using a pyrheliometer
  - ISO 9847 (1992-07) — Calibration of field pyranometers by comparison to a reference pyranometer

Standards - 2

- International Electrotechnical Commission TC82
  - IEC 60904-1 (2006-09) I-V Characterisation
  - IEC 60904-2 (2008-04) Requirements for reference solar devices
  - IEC 60904-3 (2008-04) Tabulated Solar Spectrum
  - IEC 60904-4 (2009-06) Calibration Traceability
  - IEC 60904-5 (2011-02) Determination of the equivalent cell temperature (ECT) of photovoltaic (PV) devices by the open-circuit voltage method
  - IEC 60904-7 (2008-11) Computation of Spectral Mismatch
  - IEC 60904-8 (1998-02) Guidelines Measure SR

Standards - 3

- International Electrotechnical Commission TC82
  - IEC 60904-9 (2007-10) Simulator Classification
  - IEC 60904-10 (2009-12) Methods of linearity measurement
  - IEC 60891 (1987 + 1992) Temp. & Irradiance Correction
  - IEC 61215 (2005-04) Determination of Temp. Coeff.
  - IEC 61215 + 61646 Type Approval
  - IEC 61724 (1998-04) Photovoltaic System Performance Monitoring - Guidelines for Measurement, Data Exchange and Analysis
  - IEC 61829 (1995-03) On-Site Measurement of I-V Characteristics

Standards – 4

- International Electrotechnical Commission TC82
  - IEC 61727 (2004-12) Characteristics of the Utility Interface
  - IEC 62124 (2004-10) Photovoltaic (PV) stand-alone systems Design verification
  - IEC 62093 (2005-03) Balance-of-system components for photovoltaic systems Design qualification natural environments

Standards - 5

- ASTM (American Society for Testing and Materials)
  - E927-10 Standard Specification for Solar Simulation for Terrestrial Photovoltaic Testing
  - E948-09 Standard Test Method for Electrical Performance of Photovoltaic Cells Using Reference Cells Under Simulated Sunlight
  - E973-10 Standard Test Method for Determination of the Spectral Mismatch Parameter Between a Photovoltaic Device and a Photovoltaic Reference Cell
  - E1021-06 Standard Test Methods for Measuring Spectral Response of Photovoltaic Cells

Standards - 6

- ASTM (American Society for Testing and Materials)
  - E1036-08 Standard Test Methods for Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells
  - E1040-10 Standard Specification for Physical Characteristics of Nonconcentrator Terrestrial Photovoltaic Reference Cells
  - E1125-10 Standard Test Method for Calibration of Primary Non-Concentrator Terrestrial Photovoltaic Reference Cells Using a Tabular Spectrum

Standards - 7

- ASTM (American Society for Testing and Materials)
  - E1143-05 (2010) Standard Test Method for Determining the Linearity of a Photovoltaic Device Parameter with Respect To a Test Parameter
  - E1362-10 Standard Test Method for Calibration of Non-Concentrator Photovoltaic Secondary Reference Cells
  - E1462-00 (2006) Standard Test Methods for Insulation Integrity and Ground Path Continuity of Photovoltaic Modules
  - E1328-05 Standard Terminology Relating to Photovoltaic Solar Energy Conversion

Standards - 8

- ASTM (American Society for Testing and Materials)
  - E2236-10 Standard Test Methods for Measurement of Electrical Performance and Spectral Response of Nonconcentrator Multijunction Photovoltaic Cells and Modules
  - E816-05 (2010) Standard Test Method for Calibration of Pyrheliometers by Comparison to Reference Pyrheliometers
  - E824-10 Standard Test Method for Transfer of Calibration From Reference to Field Radiometers

Standards - 9

- ASTM (American Society for Testing and Materials)
  - G130-06 — Standard Test Method for Calibration of Narrow- and Broad-Band Ultraviolet Radiometers Using a Spectroradiometer
  - G138-06 — Standard Test Method for Calibration of a Spectroradiometer Using a Standard Source of Irradiance
  - G167-05 (2010) — Standard Test Method for Calibration of a Pyranometer Using a Pyrheliometer
  - G173-03 — Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37 ° Tilted Surface

Standards - 10

- ASTM (American Society for Testing and Materials)
  - G177-03 (2008) e1 — Standard Tables for Reference Solar Ultraviolet Spectral Distributions: Hemispherical on 37 ° Tilted Surface
  - G183-05 (2010) — Standard Practice for Field Use of Pyranometers, Pyrheliometers and UV Radiometers
  - G197-08 — Standard Table for Reference Solar Spectral Distributions: Direct and Diffuse on 20 ° Tilted and Vertical Surfaces
  - G207-11 — Standard Test Method for Indoor Transfer of Calibration from Reference to Field Pyranometers

Solar radiation instruments - 1

- Thermopile
  - Pyrheliometer
    - Direct Irradiance, limited field of view (FOV)
    - Tracker needed

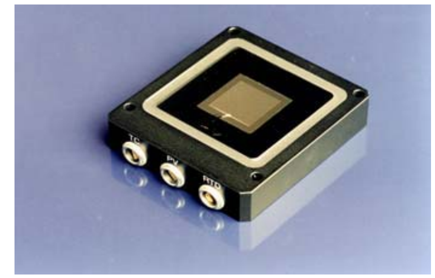
  - Pyranometer
    - Gobal (2 π sr) or 180 FOV

  - Shadow band
    - Measurement of diffuse (inplane) irradiance

Properties: Spectral range from 2500 to 4000 nm

Solar radiation instruments - 2

- Silicon detectors
  - Reference Cell (Indoor and outdoor)
    - Output either in mV or open cell (4 wires).
  - Monitoring cell
    - Output in mV measured over a shunted cell
    - Range between 20 and 60 mV @1000 W/m^2



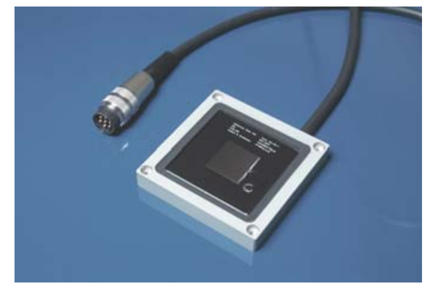


Foto: Fraunhofer FrG-Ise

Foto: A. Colli (Eurac)

Solar radiation instruments - 3

- Overview of classification of thermopile and Si detectors

Pyranometer characteristics	According to ISO 9060			Si Dectector
	Secondary standard	First class	Second class	
Response time (95% response)	< 15 s	< 30 s	< 60 s	< 10 ms
Stability (Change /year %of full range)	± 0,8 %	± 1,5 %	± 3 %	< 1 % Comparable to module degradation
Non linearity (@ 500 W/m² with respect to 1000 W/m²)	± 0,5 %	± 1,0 %	± 3 %	Neglectable
Temperature response	2 %	4 %	8 %	
Spectral sensitivity	3 %	5 %	10 %	Possible up to 10%
Directional response for beam radiation	± 0,5 %	± 2,0 %	± 5 %	

Uncertainty of responsivity value	From 2% up to 5%	From 2% upto 8%
Cost	High	Lower

Set-up of solar radiation monitoring system - 1

- Pyranometer set-up – Key requirements
  - Site
  - Instrumentation
  - Electrical connection

Set-up of solar radiation monitoring system - 2

- Site
  - Choose a location “far away” from any obstacles (trees, steep terrain and buildings)
    - Practical: unobstructed view of the sky from zenith angle 0° to 60°
    - Horizon lower than 30° above characterisation site
  - Stable horizontal platform to mount the pyranometer(s)
  - Easy accessible (to perform instrument check and maintenance)

Set-up of solar radiation monitoring system - 3

- Instrumentation
  - Avoid humidity inside the pyranometer case
    - Check color of Silica cartridge
    - Remove the cartridge, if necessary, to exchange the Silica
    - Change cartridge seal (“O” ring if moisture keeps building up
    - Use grease (Vaseline) to keep “O” ring in soft conditions
  - Pyranometer dome
    - Free of scratches
    - Daily check / clean the dome using soft cloth or household paper and a solvent (eg. Propanol)
  - Optional ventilation unit reduces the thermal offsets and keep the dome free of dew

Set-up of solar radiation monitoring system - 4

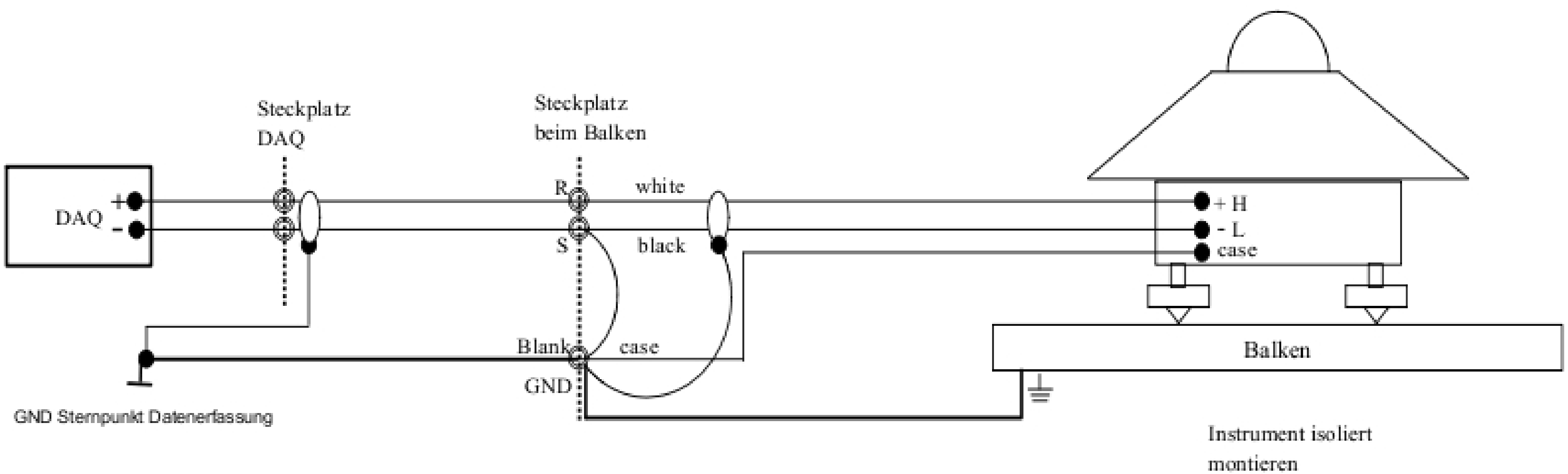
- Electrical

  Avoid ground loops (i.e no electrical connection between the earth of the mounting plate and the earth/ground of the data acquisition system (voltmeter/data logger).

  – Pyranometer isolated from mounting surface
    - Thermopile high and low signal must be isolated from ground
    - Cable shield connected to pyranometer case
    - Connect low to GND

  – Pyranometer grounded via mounting surface
    - Thermopile high and low signal must be isolated from ground
    - Connect low to GND
    - Check if shield is connected to pyranometer case
      – Yes -> do not connect shield to GND
      – No -> connect shield to GND

Set-up of solar radiation monitoring system - 5



Calculation of Global Irradiance

$$Irr_{global} = U_{tp}/S$$

- Where:
  - Irr_{global} : Global Irradiance
  - Utp : thermopile voltage [μV]
  - S : sensitivity factor [$\mu V/(W/m^2)$]

Calculation of Reference Irradiance

$$Irr_{global} = Irr_{direct} * \cos(\alpha) + Irr_{difuse}$$

- Irr_{global} : Global Irradiance
- Irr_{direct} : Direct irradiance from reference pyrheliometer
- $Irr_{diffuse}$: Diffuse irradiance from shaded pyranometer
- α : Zenith angle

PV Measurements - 1

- Indoor / Outdoor
  - Equipment
    - Simulator (Flash or continuous light source)
      - Issues with area / non uniformity / heating
    - Reference device
      - Selection of reference cell to match Spectral match.
    - Temeprature reading
    - Load
      - Resistive / Electronic
      - Cabling (“Kelvin” (4 Wire))
    - Data acquisition system
      - Fast (flash simulators)
      - Slow (triggered voltmeters)

PV Measurements - 2

- Indoor / Outdoor
  - Spectrum
    - According to IEC 60904-8
    - Measuremnt of Spectral responsivity of PV devices
      - Indoor either by bandpass filters or chopped monochromatic light
    - Measurement of Spectral irradiance
      - Indoor / Outdoor
        - » Spectral radiometers (Fast / Slow)
        - » Spectral range (up to 1200 nm (Si based material), higher for multi junction devices
  - Correction of measured I_{sc} for spectrum
    - According to IEC 60904-7

PV Measurements - 3

- Indoor / Outdoor
  - Spectrum
    - According to IEC 60904-8
    - Measurement of Spectral responsivity of PV devices
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    - According to IEC 60904-7

PV Measurements - 4

- Correction from measurement to STC conditions
  - According to IEC 60891 (correction for Irradiance and Temperature)

PV Array Measurements - 1

- Measurement of Current – Voltage characteristics of medium and large size PV arrays
- Extrapolation to STC (1000 W/m^{-2}, 25°C and spectral irradiance distribution according to IEC60904-3)
- Measurements according to IEC 61829
- Efficient way to determine module or string mismatch conditions, connection and cabling errors as well as module failures or degradation.

PV Array Measurements - 2

- Measurement Procedure
  - 2 methods for on-site measurements using IEC 609891 for temperature and irradiance correction
    - Method “A”:
      - Use effective array junction temperature
    - Method “B”:
      - Derives Tj from Voc measurements at different irradiance levels and Ambient Temperature
      - It overcomes the difficulty of mounting temperatures sensor (building integrated PV)
      - More measurements needed at lower irradiance levels (morning and afternoon)

PV Array Measurements - 3

- Extrapolation procedure
  - Method consists in a scaling transformation of the I-axis by the ratio of the irradiances
  - Simultaneous displacement along the V-axis by DV
    - while the procedure of IEC 60891 corresponds to a displacement by DI parallel to the I-axis only.
    - It’s more convenient to use the scaling since then the extrapolation is done up to open circuit conditions.

PV Array Measurements - 4

- Current Extrapolation
  - The extrapolation of the current measurements to STC is done by multiplying the actual current readings with the factor 1000/H
  - Temperature corrections on the currents of the reference device and of the arrays under test may be neglected.
    - A large temperature difference (i.e. more than 10° C) between the reference device and the modules would cause less than 1% error in the value of the extrapolated current.
    - T_coefficient of Isc is very small (ca. 500 ppm/°C for crystalline material).
  - The Spectral mismatch between reference device and module(s) could be minimized by using a reference device of the same type as the module(s) of the array.

PV Array Measurements - 5

- Voltage Extrapolation - 1
  - The voltage data have to be extrapolated to STC by adding to the actual values a correction term (DV)
  - Takes into account both the effects of the temperature and the irradiance.
    - $Voc\_{STC} = V_{oc\_m} * (1+DV)$
    - $DV = a * \ln(G_{STC}/H) + c * H + b * (T_a – T_{STC})$
      - $a = (1/V_{oc})\ \delta V_{oc} / \delta(\ln(H)$
      - $b = (1/V_{oc})\ \delta V_{oc} / \delta T$
      - $c = b * \delta Tj / \delta H$
      - with Tj is the mean junction temperature (ECT).

PV Array Measurements - 6

- Voltage Extrapolation -2
  - From the V_{oc} vs. irradiance measurements, together with the V_{oc} data during the actual power scans, the coefficients a, b and c should be chosen such as to minimize the scatter (standard deviation) of the resulting V_{oc_STC} values.
  - Start with a value of a = 0.06, b = -0.004 [$°C^{-1}$] and c = 0.12 [m^2kW^{-1}].

PV Array Measurements - 7

- Final Extrapolation - 1
  - During rapid irradiance fluctuations the assumption of thermal equilibrium (on which the expression for Dv is based) is not very good
    - scatter in the values of V_{oc_STC}
    - systematic errors
      - over estimation of V_{oc_STC} during periods of increasing irradiance (in the morning)
      - underestimation during periods of decreasing irradiance.
  - Such scatter can be reduced considerable if V_{oc} data are taken with low and/or slowly varying irradiance.

PV Array Measurements - 8

- Final Extrapolation - 2
  - Applying the irradiance and temperature corrections to all points of the measured characteristic, we obtain the extrapolated I-V curves at STC using the formulas (Eq 4. and 5.)
    - $I_{STC} = I_{\_m} * (H_{STC}/H)$ (4)
    - $V_{STC} = V_{\_m} + Dv - R_s * (I_{STC} - I_{\_m})$ (5)
      - $Dv = V_{oc\_STC} - V_{oc\_m}$ i.e. the difference between the V_{oc} obtained during the scan and that determined by the method described above.
      - R_s is the series resistance of the array and the cabling. The value of R_s can be found by measuring the I-V characteristic of an array at two different irradiance levels (preferably one measurement around 600 W/m² and the other around 1000 W/m²)
      - correct both curves to STC and varies the value of R_s in the formula until both corrected curves give the best match.

PV Array Measurements - 9

- Final Extrapolation - 3
  - The fill factor is found using the reduced characteristics i = f(u) at the maximum power point ($i_{\_mp}$, $v_{\_mp}$).
    - FF_{STC} = $FF_{\_m} + i_{\_mp} * (1-u_{\_mp}) * DV – i_{\_mp^2} * r * (H_{STC} / H-1)$
      - Isc = i
      - $V_{STC} = V_{\_m} + (1-V_{\_m}) * DV - i * r * (H_{STC}/H-1)$.
  - From these values we now can determine the rated power at STC (Standard Test Conditions):

$$P_{max\_STC} = FF_{STC} * V_{oc\_STC} * I_{sc\_STC}$$

PV Array Measurements - 10

- Practical results - 1

String	V_{oc}	G	T_a	D_V	V_{oc_STC}
id.	[V]	[W/m^2]	[°C]	[V]	[V]
F38	929.4	452	0.9	19.49	948.9
F38	894.6	858	6.6	54.77	949.4
F37	932.7	452	1.0	19.34	952.0
F37	900.3	855	6.6	54.95	955.2
F35	928.7	449	1.0	19.22	947.9
F35	887.7	857	6.6	55.08	942.8
F34	929.4	449	1.0	19.22	948.6
F34	888.6	858	6.7	55.39	944.0
F33	931.5	449	1.0	19.23	950.7
F33	891.5	857	6.9	56.34	947.8
F32	934.3	449	1.0	19.23	953.5
F32	898.4	861	7.3	56.46	954.9

The table shows the results of the determination of V_{oc_STC} for each string (consisting in 22 Modules of 72 cells in series).

With

a = 0.052,

b= -0.0035 [°C^{-1}]

c = 0.14 [m^{2}kW^{-1}].

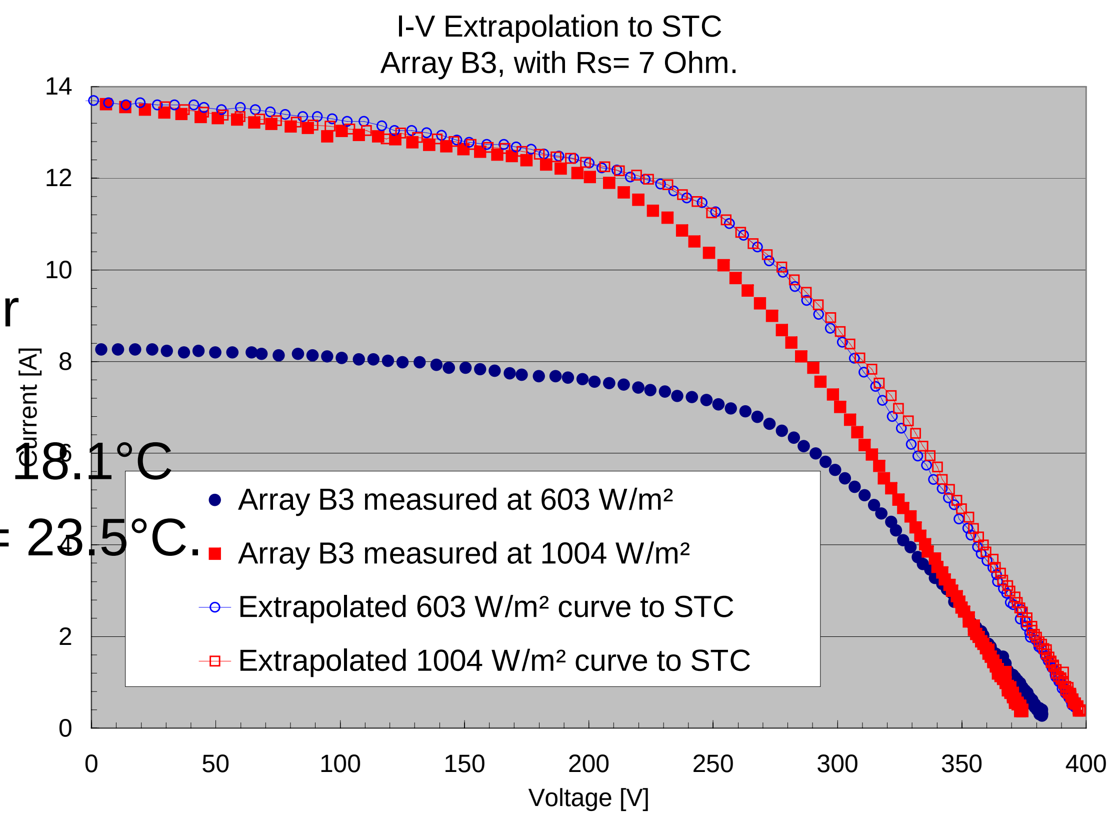
PV Array Measurements - 11

- Practical results – 2

Extrapolation to STC of two measurements carried out on the same array (B3) under different ambient conditions

Scan1: 603 W/m²; Ta = 18.1°C

Scan2: 1004 W/m²; Ta = 23.5°C.



The extrapolated P_{max_STC} of both scans with a value of R_s = 7 Ohm resulted in a 2828 W (603 W/m² scan1) and 2832 W (1004 W/m² scan2)

Difference of 4W!

PV Array Measurements - 12

- Uncertainty estimation -1
  - The uncertainty is dependent on the used equipment, irradiance reference device and ambient conditions. The following table give guidelines in the estimation of the final uncertainty and is not conform the ISO – GUM

Uncertainty source	Photovoltaic	Photovoltaic	Fill factor	Fill factor
[± %]	Current	Voltage	I/Isc	V/Voc
Data acquisition system	0.1	0.1	0.14	0.14
Shunt / Voltage Div	0.5	0.5	0	0
Temperature (25 ± 2°C)	0.5	2.0	0	0
Calibration of ref. device	3.0	2.0	0	0
RMS	**3.1**	**2.9**	**0.14**	**0.14**

PV Array Measurements - 13

- Uncertainty estimation -2
  - From table we may conclude that the overall uncertainty of P_{max_STC}, is the RMS value of the Current, Voltage and both Fill Factor (current and voltage) uncertainties.
  - Therefore the uncertainty in P_{max_STC} =

$$[(3.1)^2+(2.9)^2+(0.14)^2+(0.14)^2]^{1/2} = 4.2\ \%$$

PV Array Measurements - 14

- Uncertainty estimation -3
  - The main uncertainty in the determination of P_{max_STC} is therefore due to the extrapolation of the Isc
  - It requires a calibrated irradiance reference device, with the same spectral and spatial characteristics as the modules of the array.
  - Systematic errors in the calibration of the current and voltage channels of the data acquisition system have a direct effect of the absolute values of I_{sc}, and V_{oc}
  - These effects drop out completely from the determination of the fill factor.
  - The overall uncertainty in the P_{max} of < 5% might still be on the low side. A thorough analysis in accordance with the GUM might change that value.

Traceability

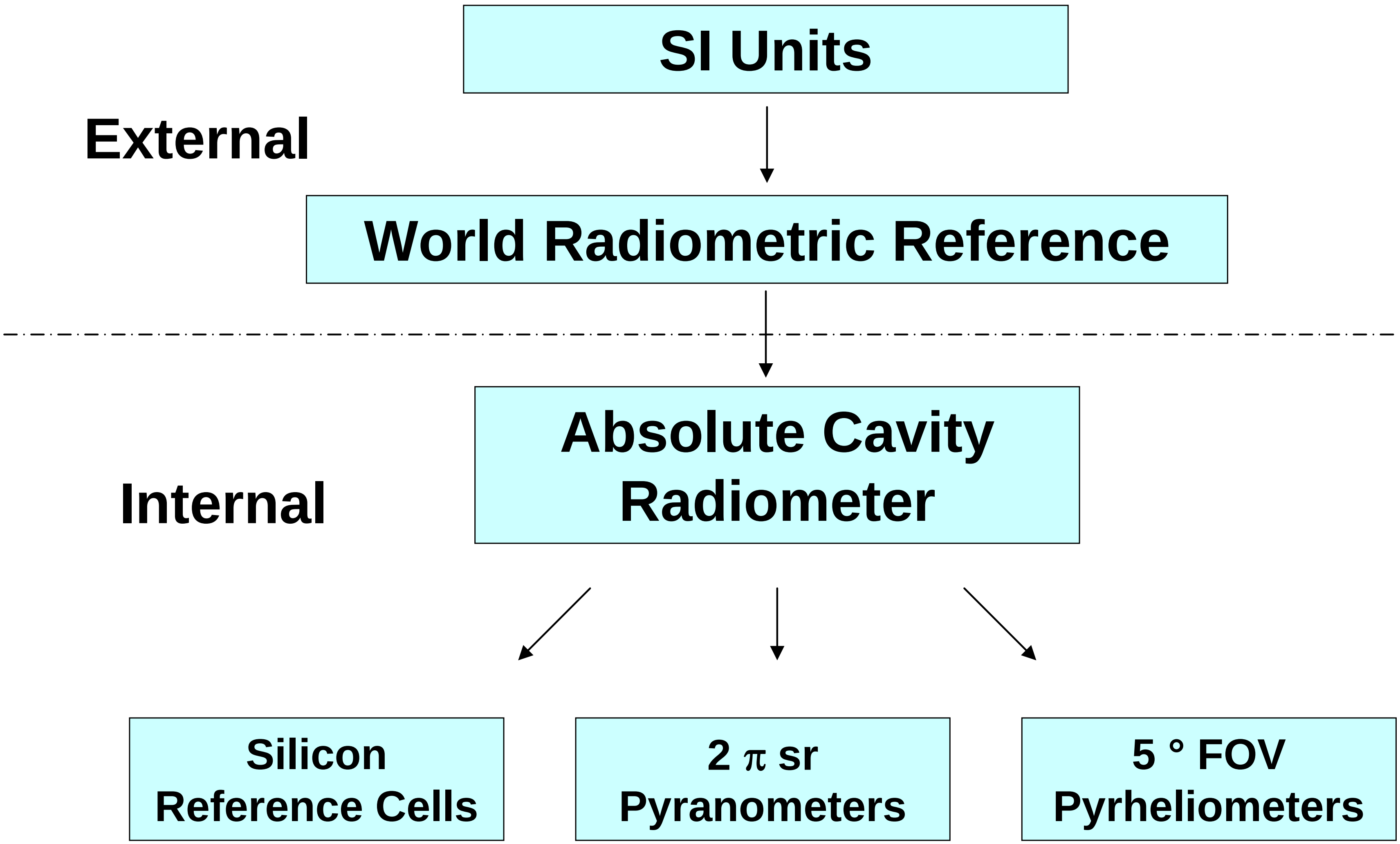
- Description according to ISO 17025

5.6.2.1.1

….to ensure that calibrations and measurements made by the laboratory are traceable to the “International System of Units (SI)” (Système international d’unités).

Unbroken chain of calibrations or comparisons linking them to relevant primary standards of the SI units of measurement.

Traceability of Irradiance



Traceability of Irradiance

SI Units

↓

Estimated Absolute Uncertainty: ± 0.3% rect. -> 0.173% (1σ)

World Radiometric Reference

PMOD Davos (CH)

External

Periodicity: 5 years

Next IPC: Sept 2015

Uncertainty: ± 0.08 % (1σ)

Internal

↓

Absolute Cavity Radiometers

Traceability of Irradiance