OPTIMUM USE OF THE LOSS FACTORS MODEL (LFM) FOR IMPROVED PV PERFORMANCE MODELLING

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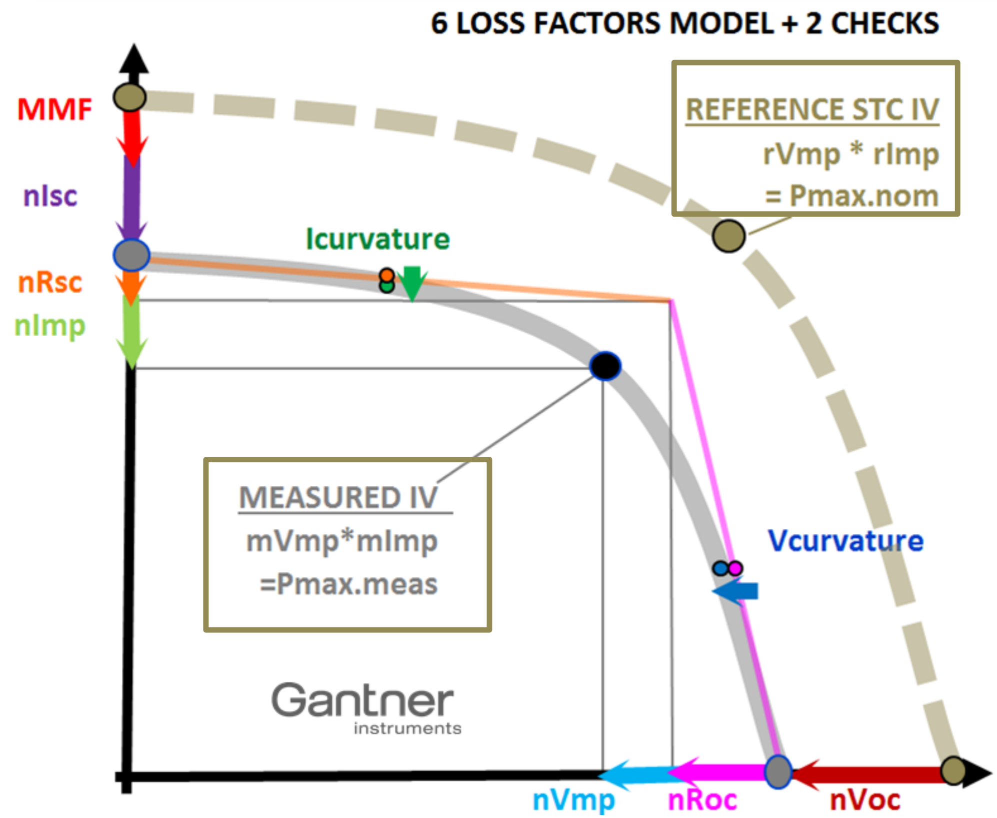
PVSAT 13 Bangor, Wales 5-7 Apr 2017

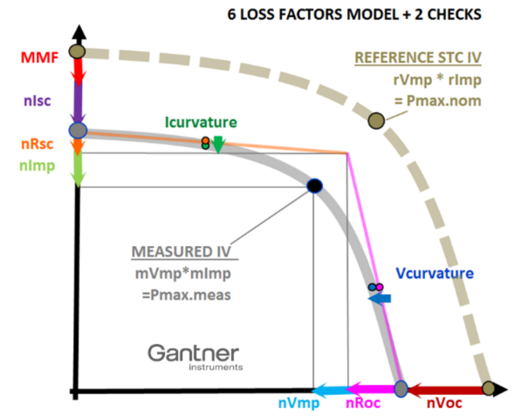
1) What is the Loss Factors Model (LFM)?

- PV performance model
  - 6 normalised, independent, significant losses based on IV curves (indoor or outdoor).
- Normalised efficiency PR_{DC} or MPR = product of 6 LFM parameters.
- 2 curve checks quantify faults
  - $I@V_{MP}/2$
    cell breakage/mismatch
  - $V@I_{MP}/2$ rollover (non ohmic contact).
- Fits all PV technologies
  - e.g. c-Si vs TF, OPV etc.

$$\eta_{MEASURED}/\eta_{NOMINAL.STC} = nI_{SC} \times nR_{SC} \times nI_{MP} \times nV_{MP} \times nR_{OC} \times nV_{OC}$$



2) What the LFM can do



- **PV manufacture optimisation**
  - e.g. how much P_{MAX} is lost due R_{SERIES}?
  - Should/could it be improved?
- **Quantify module tolerance and variability e.g. nI_{SC} = 99 ± 3%**
  - quickly identifies any atypical modules
- **Generate modelling coefficients**
  - Low light/ STC efficiency (η@0.2/ η@1.0 kW/m²)
  - plot vs. T_{MODULE} for gamma γ (%P_{MAX}/K) etc.
- **Quantify any degradation and identify its causes**
  - e.g. I_{SC}, V_{OC}, FF R_{SHUNT} falling
  - mismatch, rollover or R_{SERIES} rising
- **Predict energy yield with site dependent climate data**
- **Can work at module, string, combiner, inverter, station and site level**

3) How the LFM differs from of other models

Curve fit e.g. 1-diode models (de Soto et al)

- "Best fit" IV curve with I_{SC0}, R_{SHUNT}, R_{SERIES}, I_O and nf
- R_{SHUNT} hard to extract
- Perfect fit impossible with non-uniformities, degradation etc.
- Fit can depend on optimisation algorithm used
  (e.g. whether IV points are weighted near V_{MP} or not)

Point models e.g. SAPM (Sandia Array Performance Model)

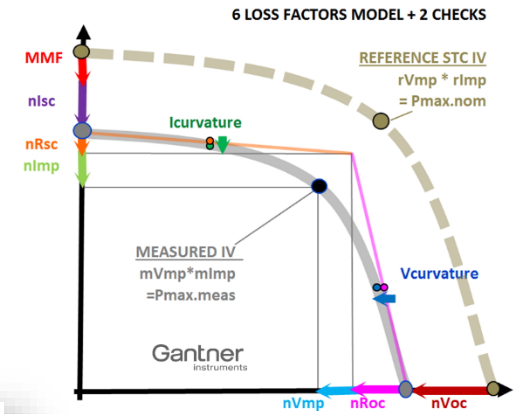
- ~29 parameters to fit the I_{SC}, I_{MP}, V_{MP}, V_{OC} and temp. coeffs (%/K).
- R_{SC} and R_{OC} are not modelled but are important for degradation.
- Most parameters are not normalised and many non-physical

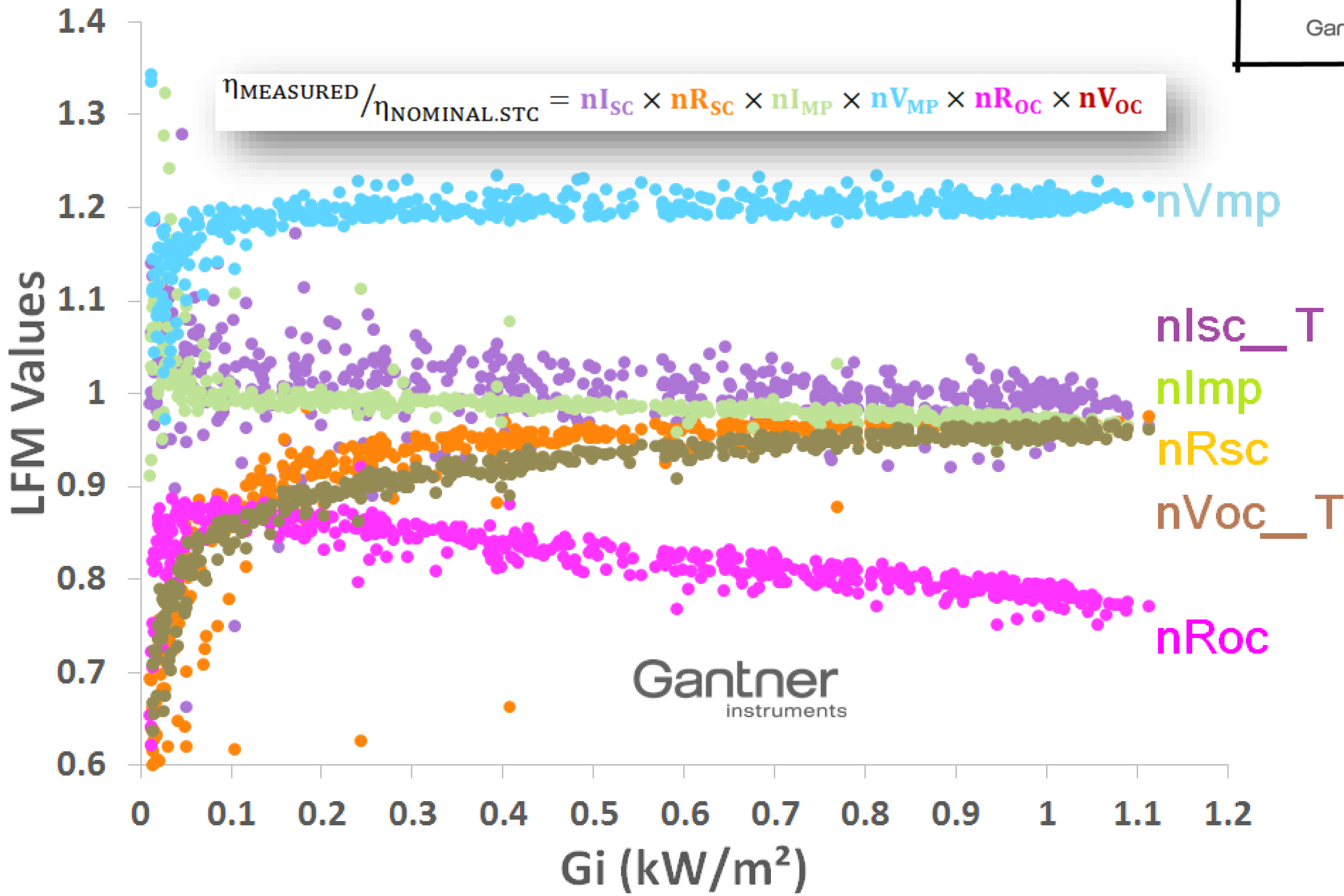
Typical LFM curves in real weather conditions

For an optimum device all lines should be near 100%

_T denotes temperature compensation

Most points on main lines, some outliers can be easily removed

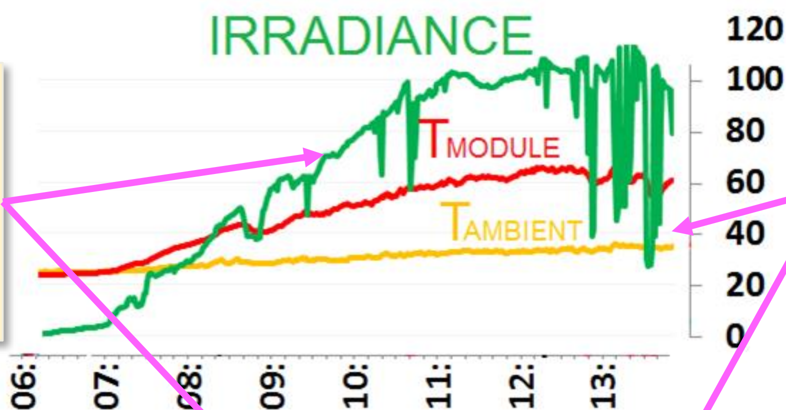




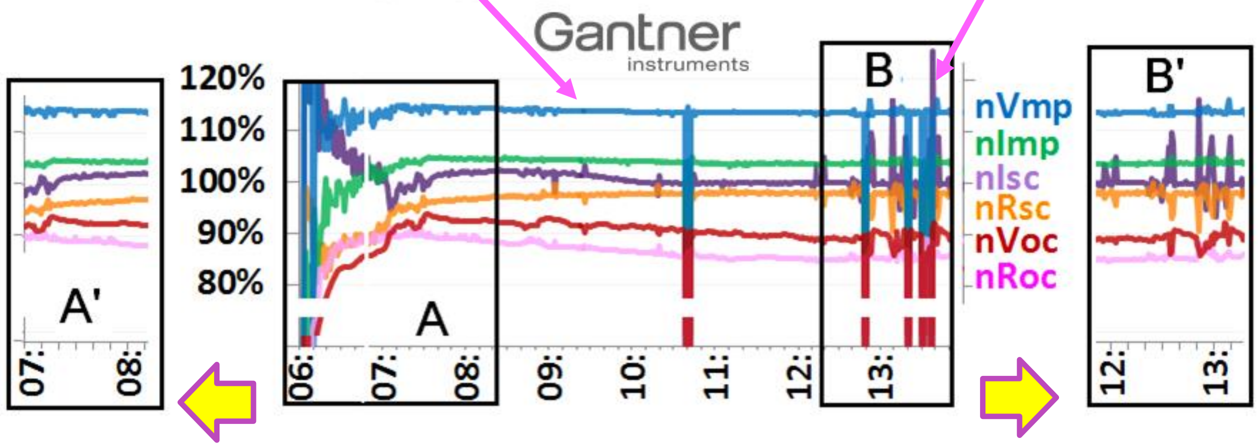
5) Monitoring LFM Values with time and data smoothing

❶ **Weather data, typical Arizona morning, mostly clear some intermittent cloud**

❷ **When irradiance steady all 6 LFM parameters were smooth and between 85% and 115% as expected.**



❸ **Intermittent irradiance (B) causes glitches in LFM parameters**



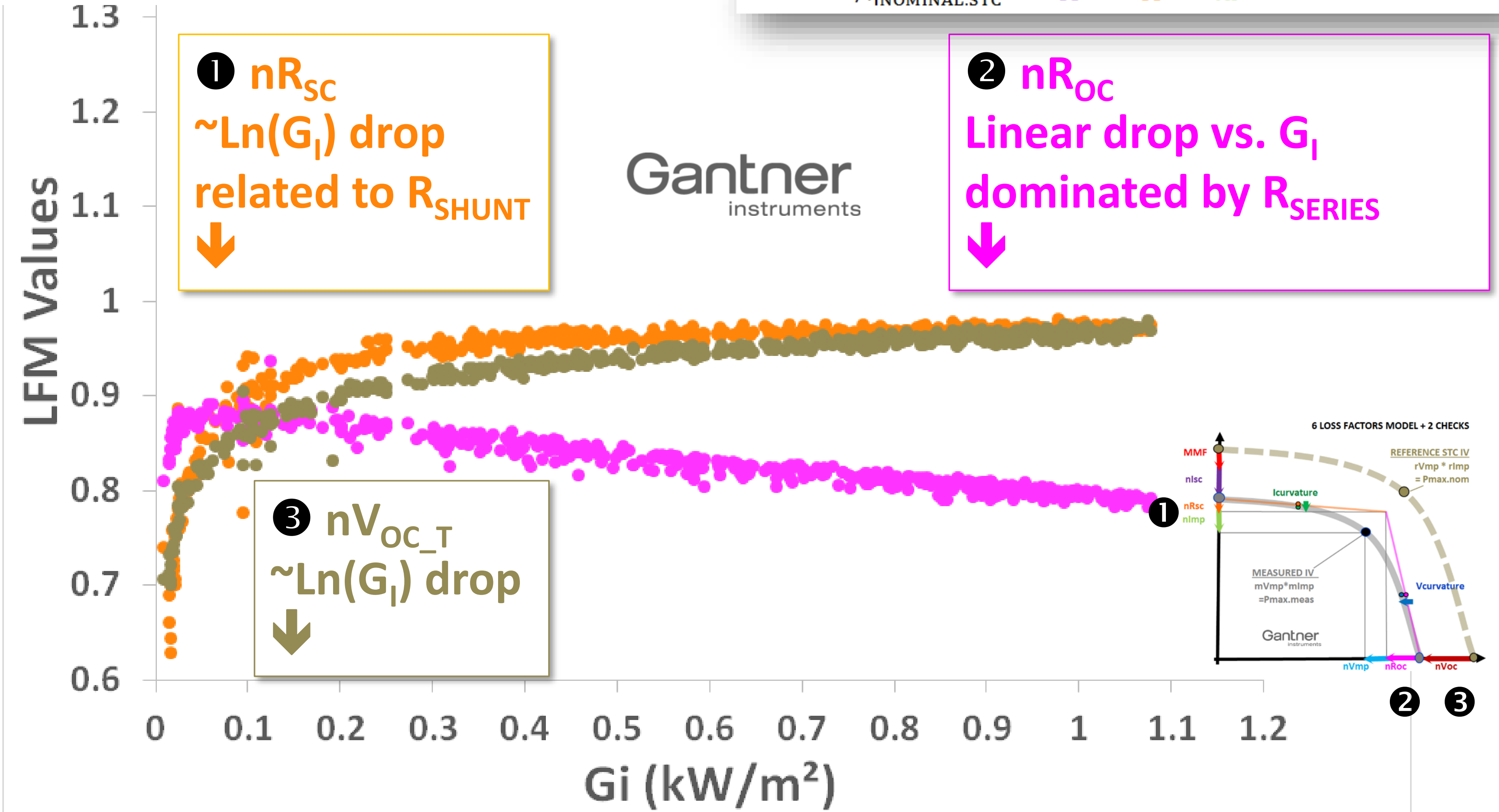
❹ **Everything is normalised so it's easy to remove glitches**

6a) Which LFM coefficients dominate efficiency vs. Irradiance?

nI_{SC}, nI_{MP} and nV_{MP} are "almost constant" with G_I

nR_{SC}, nR_{OC}, nV_{OC} cause PR_{DC} to vary with. G_I

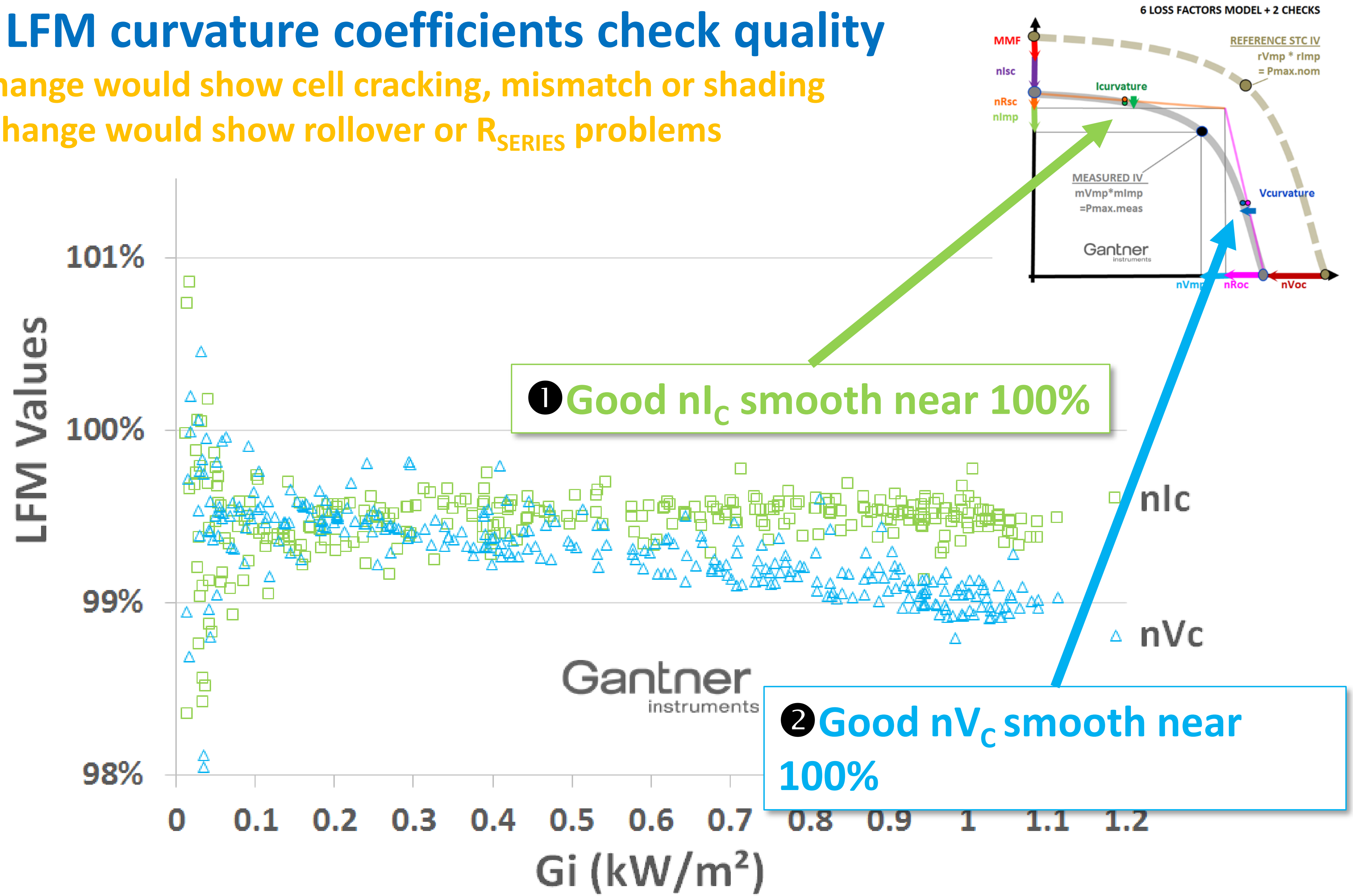
$$\eta_{MEASURED}/\eta_{NOMINAL.STC} = nI_{SC} \times nR_{SC} \times nI_{MP} \times nV_{MP} \times nR_{OC} \times nV_{OC}$$



6b) LFM curvature coefficients check quality

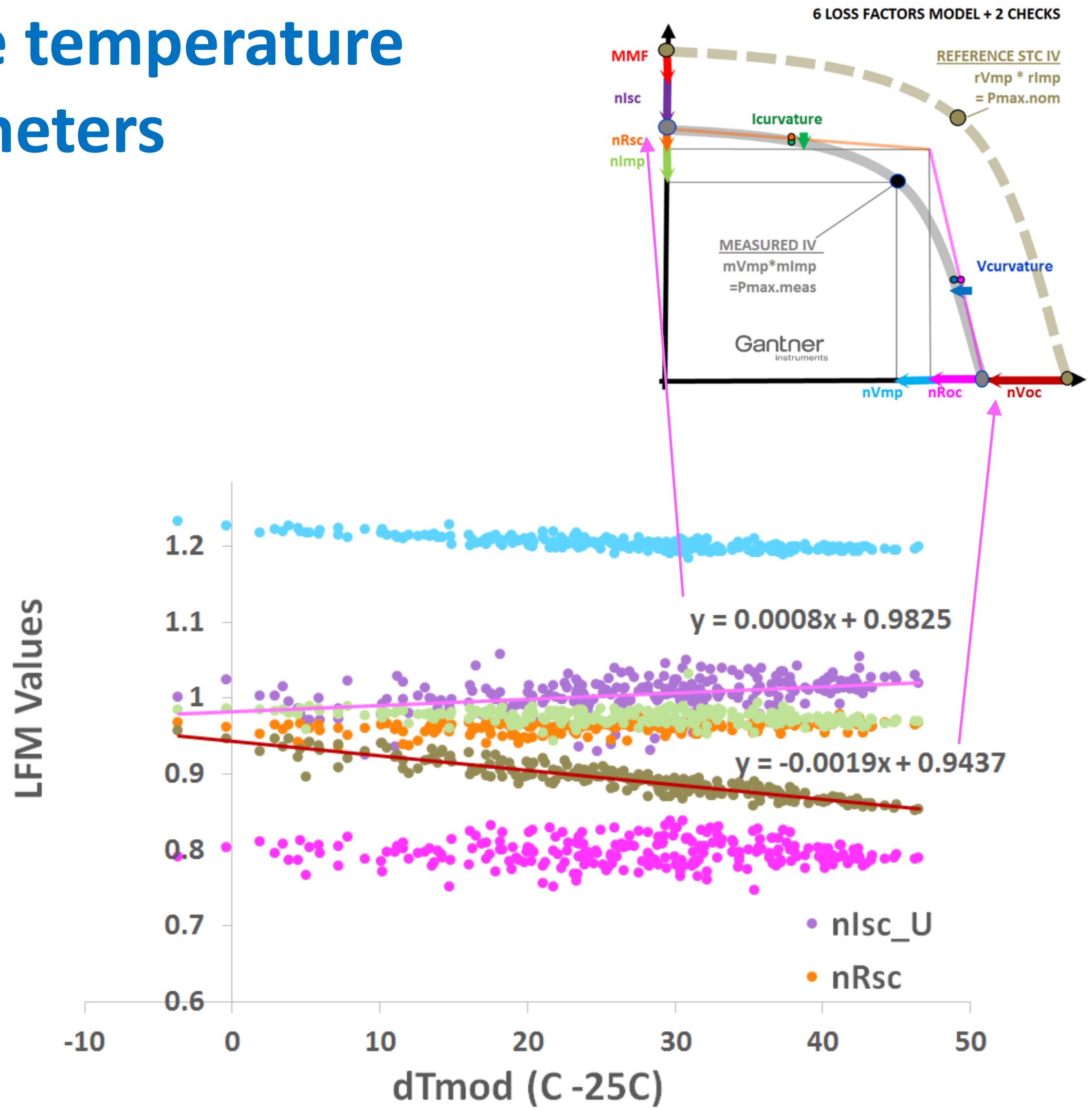
nI_C change would show cell cracking, mismatch or shading

nV_C change would show rollover or R_{SERIES} problems



7) Characterising the module temperature dependency with LFM parameters

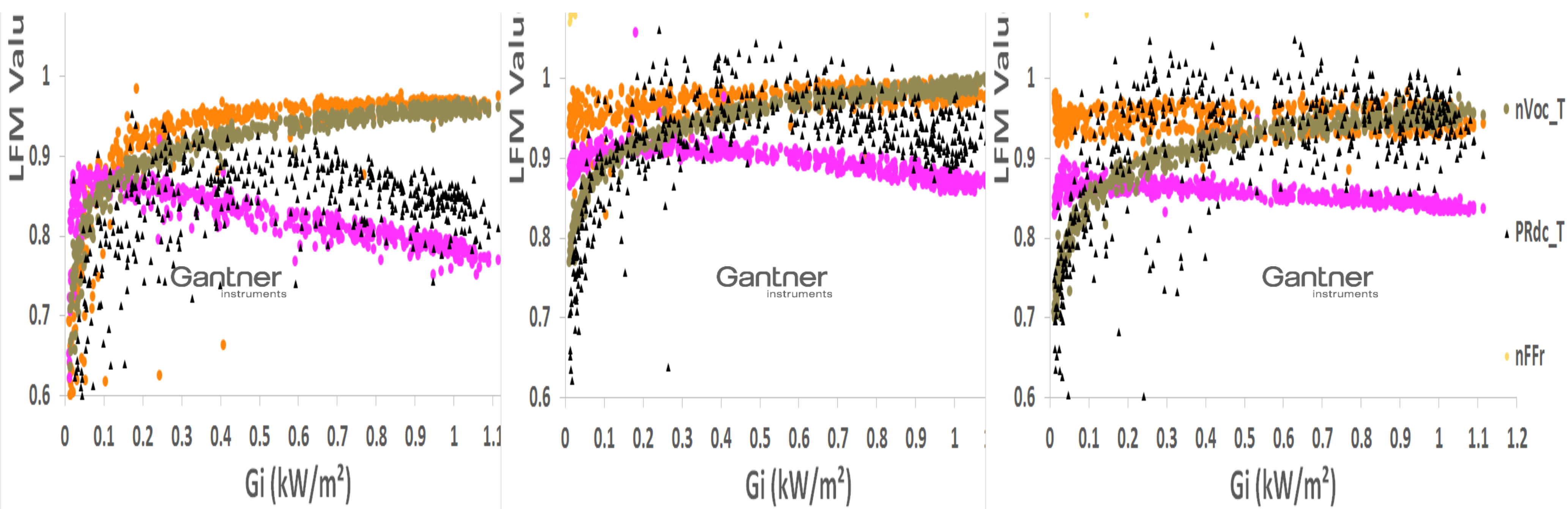
- Plot all LFM parameters vs. module temperature.
- Select "clear sky, higher temperatures and lower angles of incidence"
- Gradients then give the temperature coefficients
  $d(nI_{SC})/dT$ → alphaI_{SC}
  $d(nV_{OC})/dT$ → betaV_{OC}
  $d(PRdc)/dT$ → Gamma Pmax
- Not all parameters are temperature dependent



8) LFM coefficients vs. PV technologies - c-Si, Thin Film

How do nR_{SC}, nR_{OC}, nV_{OC} behave for different technologies?

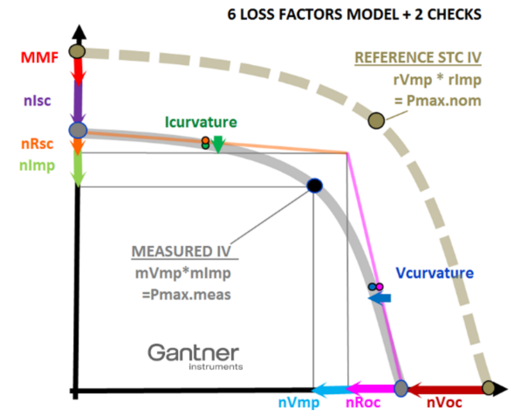
Note: $PR_{DC} \propto nR_{SC} * nR_{OC} * nV_{OC}$

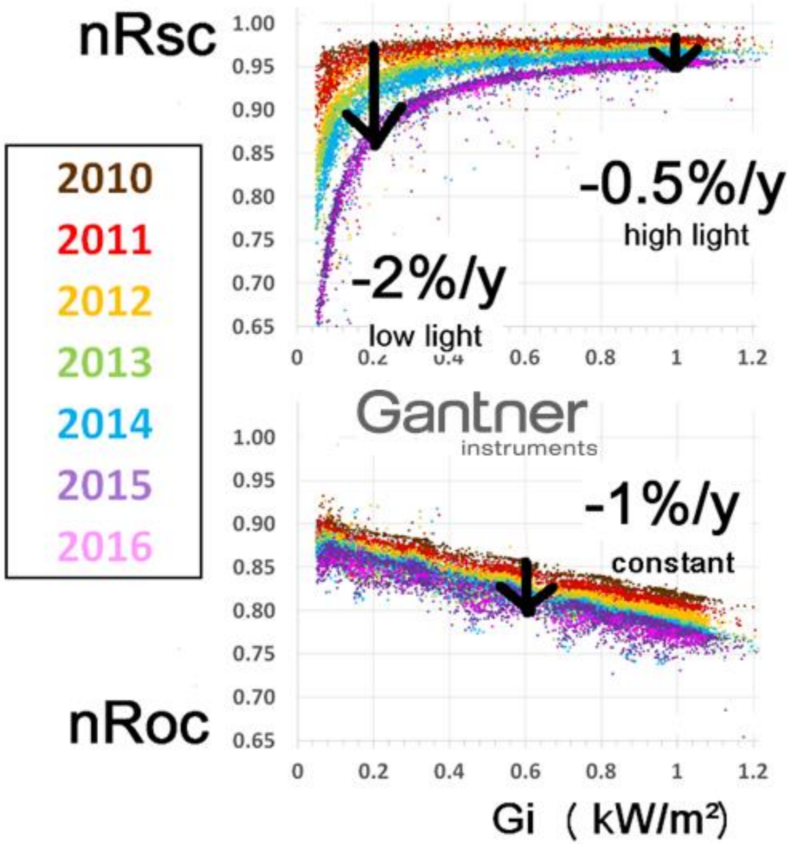


CdTe **c-Si** **a-Si:uc-Si**

9) Quantifying Degradation at different conditions from LFM parameter changes

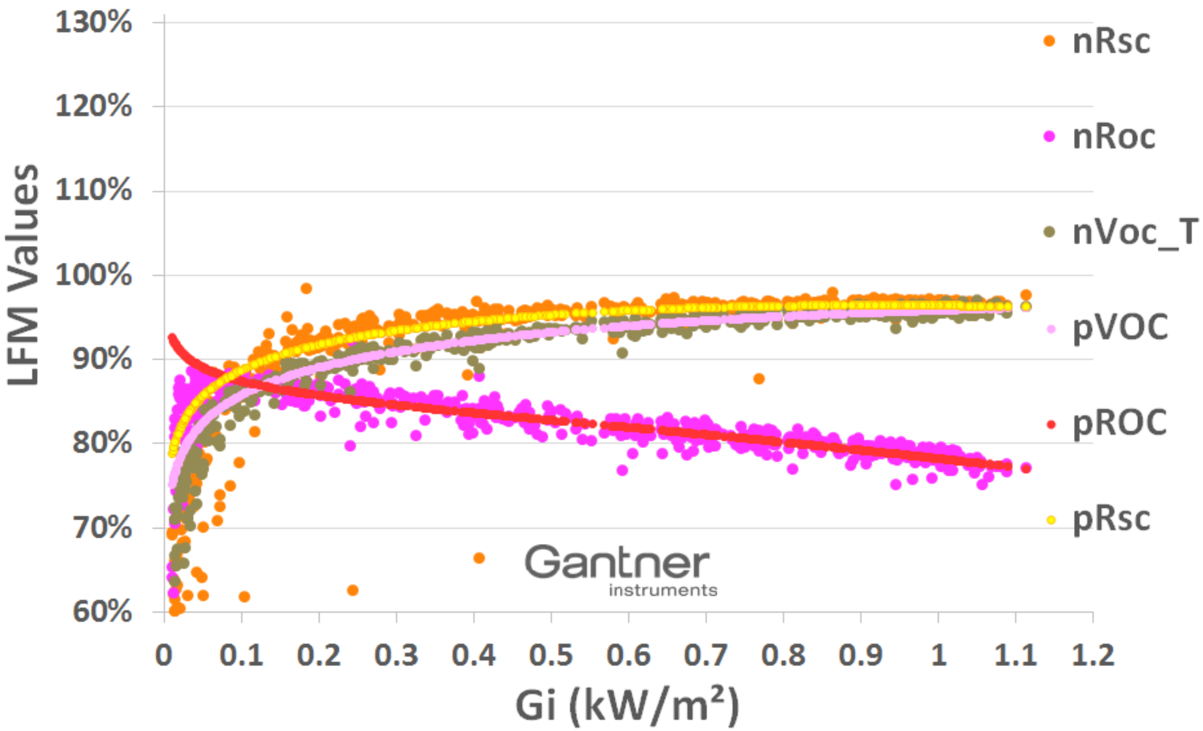
2010-2016 LFM vs. irradiance for atypical CdTe (degrading ~-3%/y)





- LFM identifies what causes degradation and the rate
- nR_{OC} -1.0%/y (all light levels)
- nR_{SC} -2.0%/y (low light)
  -0.5%/y (high light)
- Suggests a non ohmic R_{SHUNT} drop

10) Curve fitting normalised vs. predicted



- nI_{SC} is usually the most scattered and may benefit from soiling, AOI beam fraction and Spectrum corrections

All other LFM parameters are usually smooth and easy to curve fit (usually log, linear or power fit vs. irradiance)

e.g. $y = C_0 + C_1 * \ln(GI) + C_2 * GI^2$

Python code defining the LFM Parameters being put in PVLIB
Defining all LFM parameters and equations

```
nIc = mI2/(mIsc-mVmp/2/mRsc)                    # I curvature I @ Vmp/2
nVc = mV2/(mVoc-mImp/2*mRoc)                    # V curvature V @ Imp/2

mIr = (mIsc*mRsc-mVoc)/(mRsc-mRoc)              # temporary calc I @ Rsc-Roc intercept
mVr = mRsc*(mVoc-mIsc*mRoc)/(mRsc-mRoc)         # temporary calc V @ Rsc-Roc intercept

# normalised LFM parameters unit %
nIsc_U = mIsc/rIsc/Gi                           # Un temperature corrected
nRsc = mIr/mIsc                                 #
nImp = mImp/mIr*rIsc/rImp                       #
nVmp = mVmp/mVr*rVoc/rVmp                       #
nRoc = mVr/mVoc                                 #
nVoc_U = mVoc/rVoc                              # Un temperature corrected

nVoc_T = nVoc_U * (1-bVoc_Ref*( Tmod - 25)) # Temp correct
```

11) Reference Material available – from GI for PVLIB

To be published and available soon

- From GI, Tempe CdTe and c-Si

Essential Data

- Site location and orientation
- Date and time
- Irradiance (ref cell, pyr)
- Ambient, Module temperature

Optional (for corrections)

- Wind speed
- Clearness, Beam Fraction, Spectrum

Sample Python source code to import, analyse, validate and display LFM data

```
…
# DERIVE CURVATURE PARAMS
nIc = mI2/(mIsc-mVmp/2/mRsc)    # I curvature I @ Vmp/2
nVc = mV2/(mVoc-mImp/2*mRoc)    # V curvature V @ Imp/2
# CALCULATE  (mIr, mVr) WHERE RSC and ROC LINES CROSS
to make maths easier
mIr
# now calculate normalised LFM parameters unit %
nIsc_U = mIsc/rIsc/Gi           # U=Un temp corr
nRsc   = mIr/mIsc               #
nImp   = mImp/mIr*rIsc/rImp     #
nVmp   = mVmp/mVr*rVoc/rVmp     #
nRoc   = mVr/mVoc               #
nVoc_U = mVoc/rVoc              # U=Un temp corr
# also
nVoc_T = nVoc_U *  (1-bVoc_Ref*(mTmod-Tstc))        #
Temp correct by bVoc
```

www.pvpmc.org

Thanks for your attention and please get involved!

PVPerformance
MODELING COLLABORATIVE

An Industry and National Laboratory collaborative to Improve Photovoltaic Performance Modeling

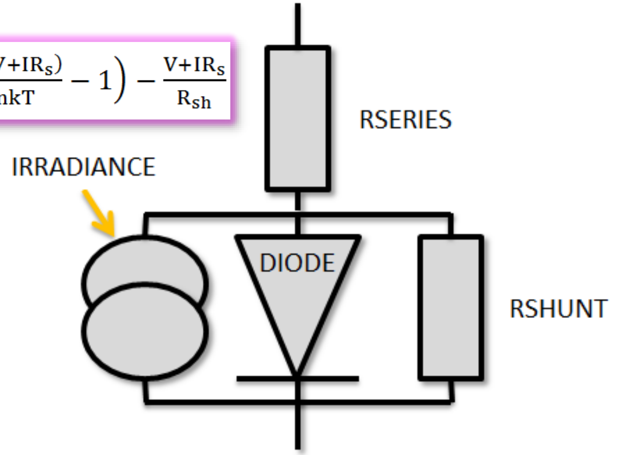
- Spare

Standard models

Curve fits e.g. 1 diode (fit equivalent circuit to IV curve)

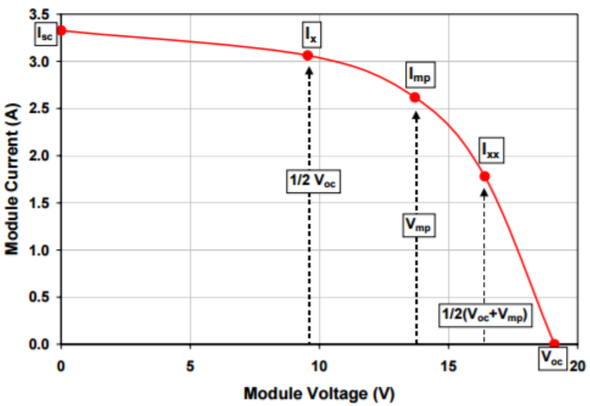
- Imperfect traces (e.g. cell mismatch) cause curve fit difficulties
- R_{SHUNT}, R_{SERIES} etc. vary with G_I , T_{MOD} (not defined in model) so can predict incorrect Low light efficiency and gamma

$$I = I_L - Io_1 . \exp\left(\frac{q(V+IR_S)}{nkT} - 1\right) - \frac{V+IR_S}{R_{sh}}$$



Point modelling e.g. SAPM (I_{SC}, P_{MP}, V_{OC} …)

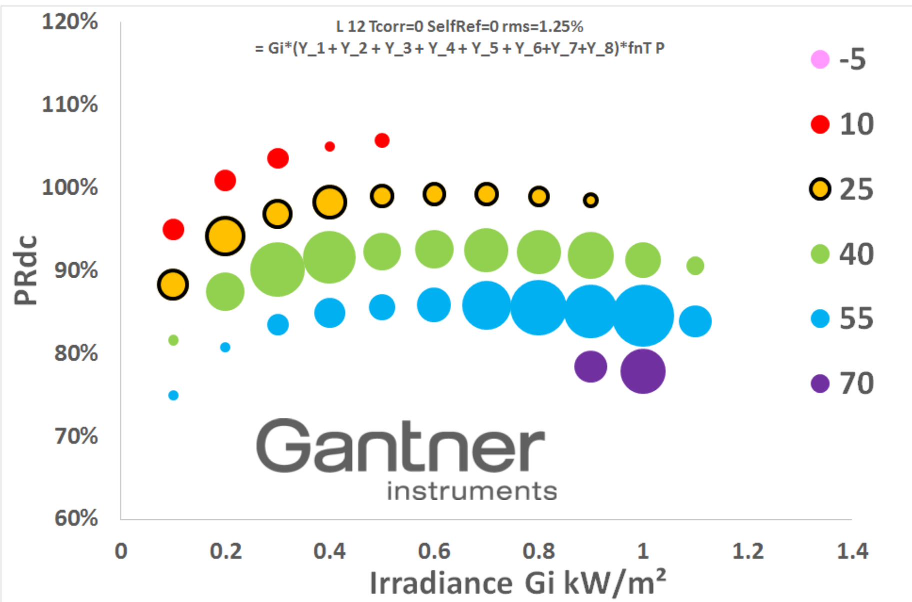
- Hard to understand – 29 coefficients including for AOI and SR
- Difficult to get a unique fit
- No modelled R_{SERIES} or R_{SHUNT}



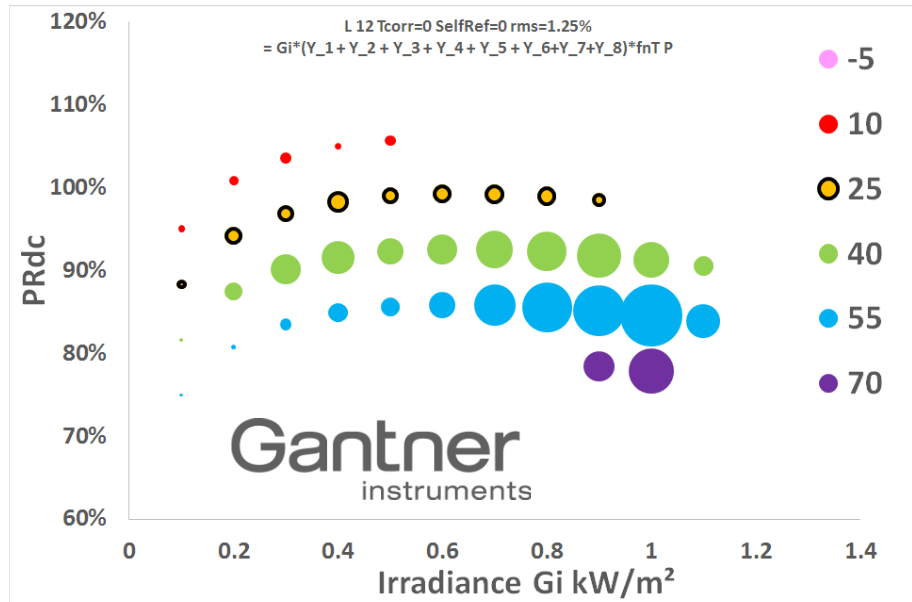
- **Neither model is normalised, their coefficients are area dependent and make it difficult to study module variability and degradation.**
- **Both models predict much more than just P_{MAX}**

Modules are characterised by "PR_{DC} vs. Irradiance and T_{MOD}" As used in simulation programs and matrix method IEC 61853

% of points / year AZ



% of energy yield / year AZ



Conclusions

- 10 Existing models have been tested
- Empirical models can be difficult to fit and may have meaningless coefficients
- LFM was used to determine optimum coefficients for a new Mechanistic Model (L) which works well

Next steps

- Further analysis- more modules, more sites
- Model spectral response, reflectivity and soiling, seasonal annealing
- Show reasons for any degradation

- If you wish to join in please send details of your model and any measurement data
- **Thanks for your attention and please get involved!**

Data required

Setup

Location : Lat, Lon, Alt

Orientation : Tilt and Azi

Module Details : Datasheet Values and Temp Coeffs

Essential :

Date+time

G_I Irradiance (by sensor type)

$T_{AMBIENT}$

T_{MODULE}

Windspeed

P_{DC}

Useful to have :

I_{DC} and V_{DC}

G_H, D_H

G_N

Spectrum, Rel Hum

I_{SC}, V_{OC}, R_{SC}, R_{OC}

Conclusions

Data required

Setup Location : Lat, Lon, Alt **Orientation :** Tilt and Azi

Module Details : Datasheet Values and Temp Coeffs

Essential :

Date+time

G_I Irradiance (by sensor type)

$T_{AMBIENT}$ T_{MODULE} Windspeed P_{DC}

Useful to have :

I_{DC} and V_{DC}

G_H, D_H G_N

Spectrum, Rel Hum

I_{SC}, V_{OC}, R_{SC}, R_{OC}

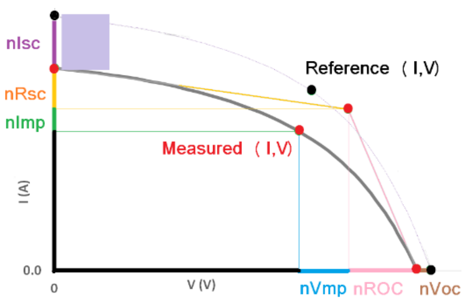
Use LFM to see which effects to model

$$PR_{DC} = [nI_{SC} * nR_{SC} * nI_{MP}] * [nV_{MP} * nR_{OC} * nV_{OC}]$$

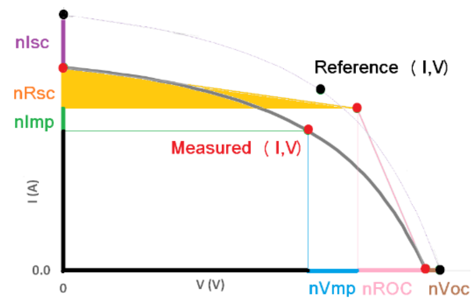
ISC ~RSHUNT ----------FF----------- ~ RSERIES VOC

Current coefficients

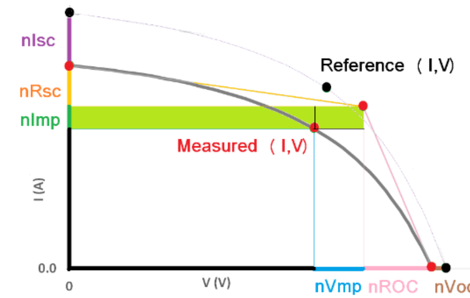
nI_{SC} ↓



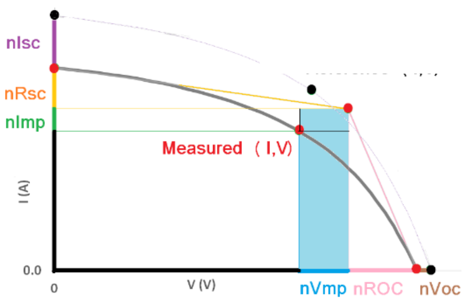
nR_{SC} ↓



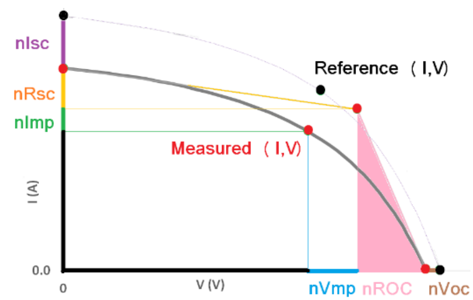
nI_{MP} ↓



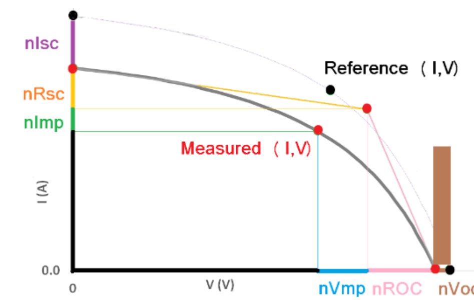
Voltage coefficients



← nI_{MP}



← nR_{SC}



← nV_{OC}

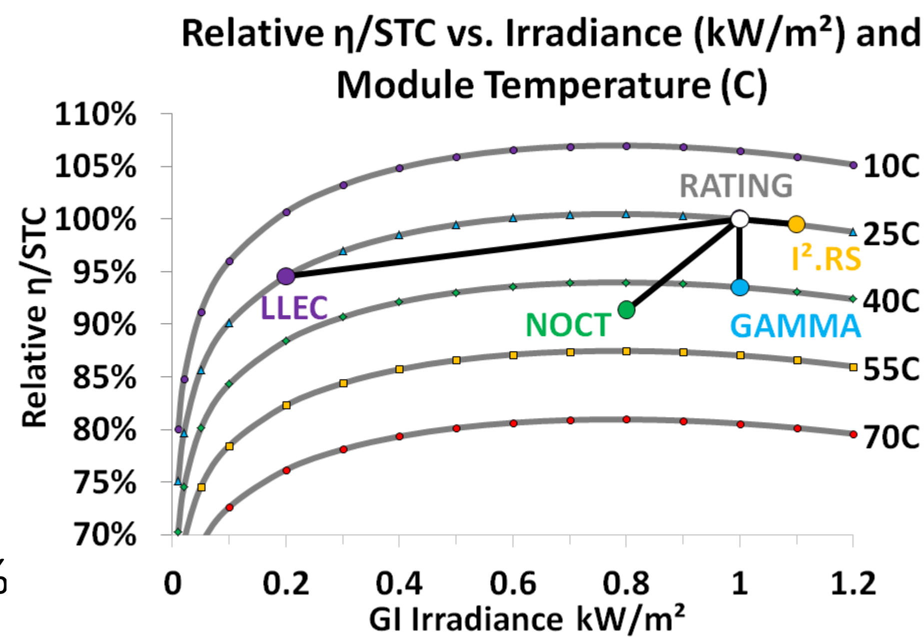
Which parameters affect PV module efficiency?

The efficiency of a PV module is dominated by

- G_I Global plane of array irradiance (kW/m^2)
- T_{MOD} Module temperature (C)

There are smaller influences from

- T_{AMB} Ambient temperature (C)
- WS Wind speed (ms^{-1})
- BF Beam/global irradiance fraction (%
- kTh Clearness index (%)
- AM Spectrum
- AOI Reflectivity vs. angle of incidence



5 coefficients needed to model performance vs. G and T