# Solar Array Power Modeling

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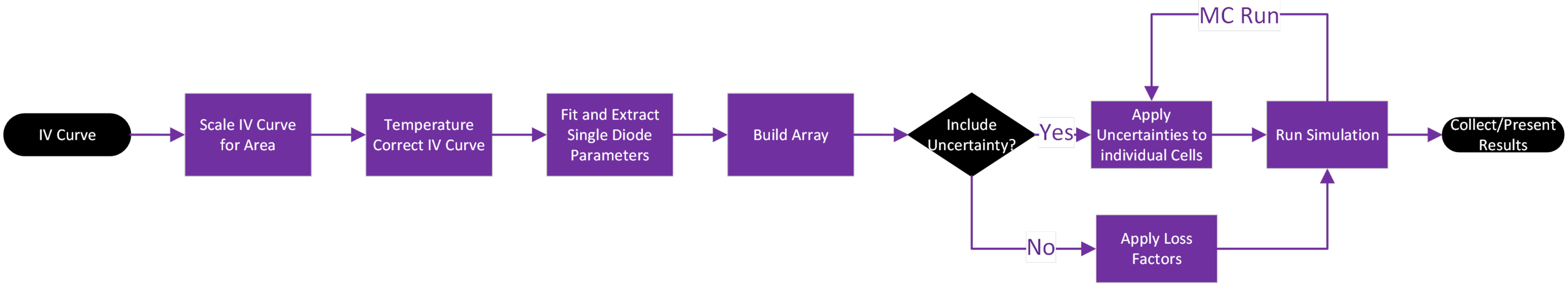
# *Goals*

- Accurately predict array performance
- Develop standard modeling capability
  - *Best Practices*
  - *Step by step procedure*
  - *Model rooted in measured data*
- Incorporate statistical values wherever possible
  - *AE9/AP9 stats*
  - *Test and Measurement Stats*
  - *Reliability*

# *Array Modeling Process Flow*

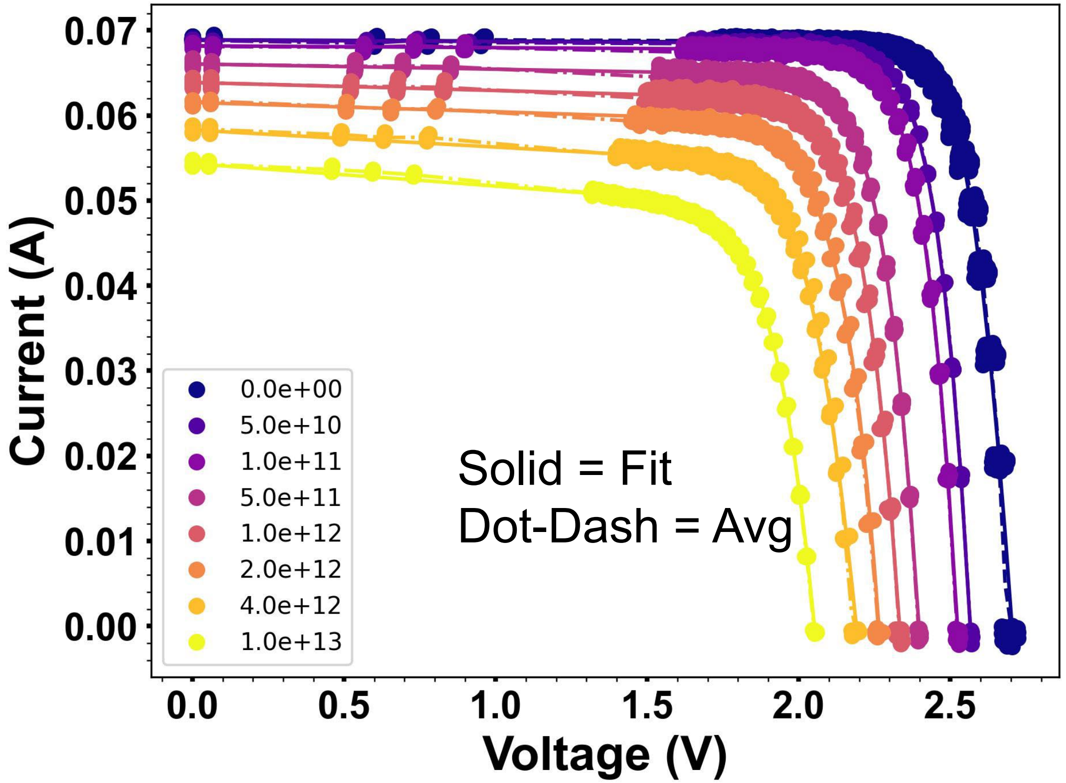


# *IV Curve*

- Data is from Aerospace 3 MeV proton radiation tests at Auburn
  - *Data was annealed to 60C Results (results available from earlier report*

- Averaging IV curves
  1. *All IV curves grouped together*
  2. *Currents and voltages are binned using voltage bins*
  3. *Current and voltage are averaged yielding current and voltage error in the IV curve average*
  4. *Average IV curve is then fit using single diode equation*

- $$I = I_{ph} - I_o e^{\left[\frac{q(V+IR_S)}{nkT}\right]} - \frac{V+IR_S}{R_{sh}}$$

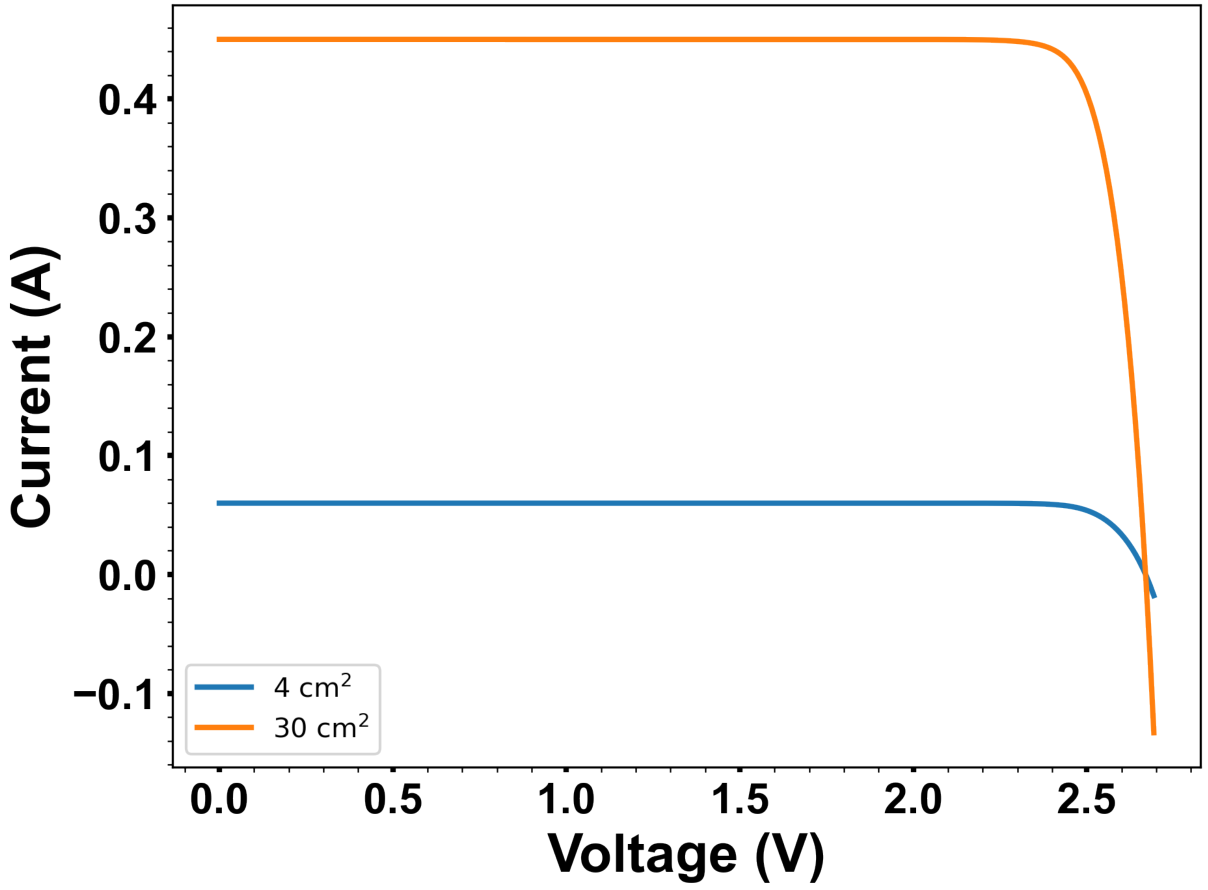



| Fluence | $I_{ph}$ | $I_0$ | n | $R_s$ | $R_{sh}$ | $r^2$ |
|---|---|---|---|---|---|---|
| 0.E+00 | 0.0689 | 6.34E-20 | 2.5090 | 1.0381 | 6828.3 | 0.9963 |
| 5.E+10 | 0.0689 | 1.46E-15 | 3.1420 | 0.3825 | 5783.6 | 0.9998 |
| 1.E+11 | 0.0682 | 4.53E-15 | 3.2063 | 0.3729 | 4608.4 | 0.9997 |
| 5.E+11 | 0.0661 | 4.03E-14 | 3.2869 | 0.4781 | 1593.0 | 0.9998 |
| 1.E+12 | 0.0639 | 4.75E-13 | 3.5134 | 0.4534 | 1061.2 | 0.9998 |
| 2.E+12 | 0.0615 | 1.14E-10 | 4.3490 | 0.0991 | 929.1 | 0.9987 |
| 4.E+12 | 0.0585 | 4.87E-14 | 3.0434 | 1.4296 | 498.2 | 0.9979 |
| 1.E+13 | 0.0544 | 2.81E-10 | 4.1668 | 0.4982 | 383.0 | 0.9996 |

# *Scale IV Curve by Area*

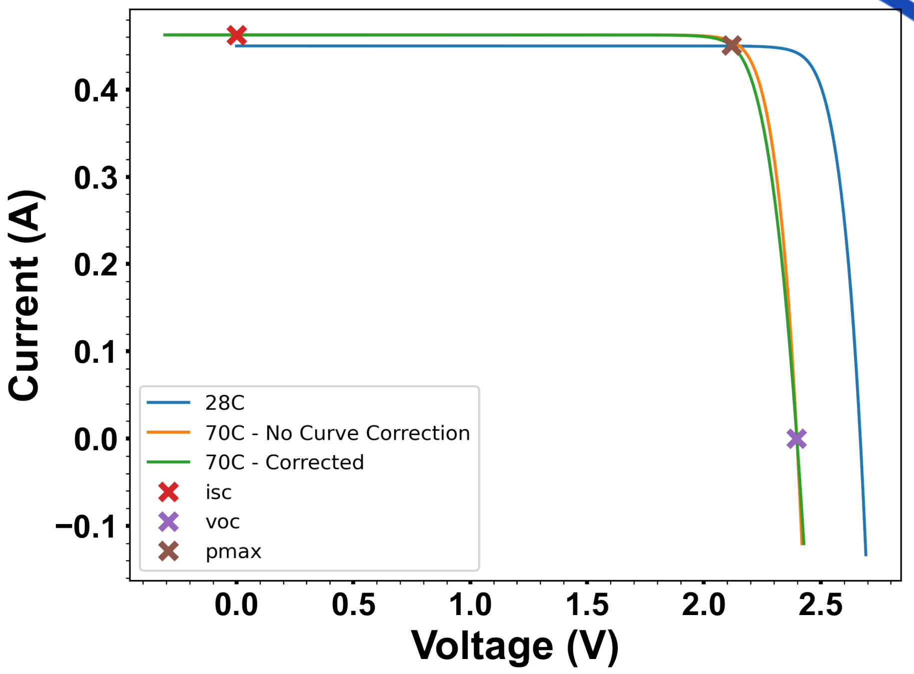
- Radiation data was collected using 4cm$^2$ solar cell data with, whereas the program cells have an area of 30cm$^2$

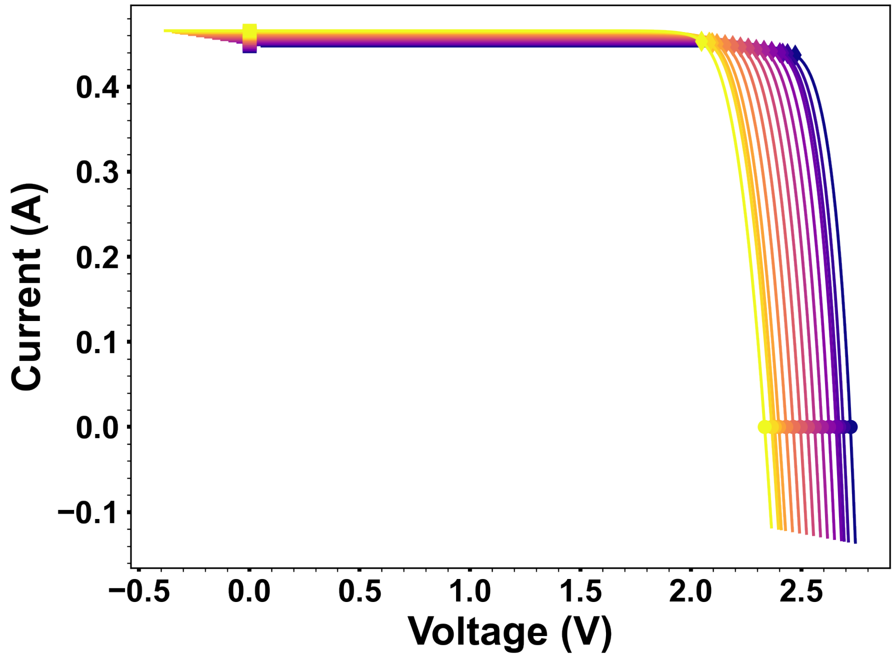
- To scale by area, the current values of the IV curve are multiplied the increase in area. This is representative of putting many 4cm$^2$ cells in parallel with each other
  - $I(V)_s = \left(\frac{I(V)}{A_m}\right) \times A_s$
  - *$V_{oc}$ Doesn't change upon area scaling*
  - *Series resistance decreases following Kirchhoff's Rules*
    - $R_s$ of 4cm$^2$ cell is 0.45Ω and when the cell is scaled to 30cm$^2$ the series is 0.06Ω



# *Temperature Correct IV Curve*

- IV curve corrected for temperature using Procedure 1 of the IEC 60891
  - *Can translate IV curve for temperature and intensity, but we only use it for temperature translation*
  - $I_T = I_i + I_{sc_i}(G_s - 1) + \alpha(\Delta T)$
  - $V_T = V_i - R_s(I_T - I_i) - \kappa I_t(\Delta T) + \beta(\Delta T)$
  - $I_T, V_T$ = *Temperature corrected current and voltage*
  - $I_i, V_i$ = *Initial current and voltage*
  - $\alpha, \beta$ = *Current and voltage temperature coefficient*
  - $\Delta T$ = *Delta between initial and final temperature*
  - $I_{sc_i}$= *Short circuit current of initial IV curve*
  - $R_s$= *Series resistance*
  - $G_s$= *Intensity scaling factor*
  - $\kappa$ = *curve correction factor*
    - Found through fitting initial IV curve and minimized on the error of the calculated meta data ($I_{sc}$, $V_{oc}$, $I_{max}$, $V_{max}$, and $P_{max}$)



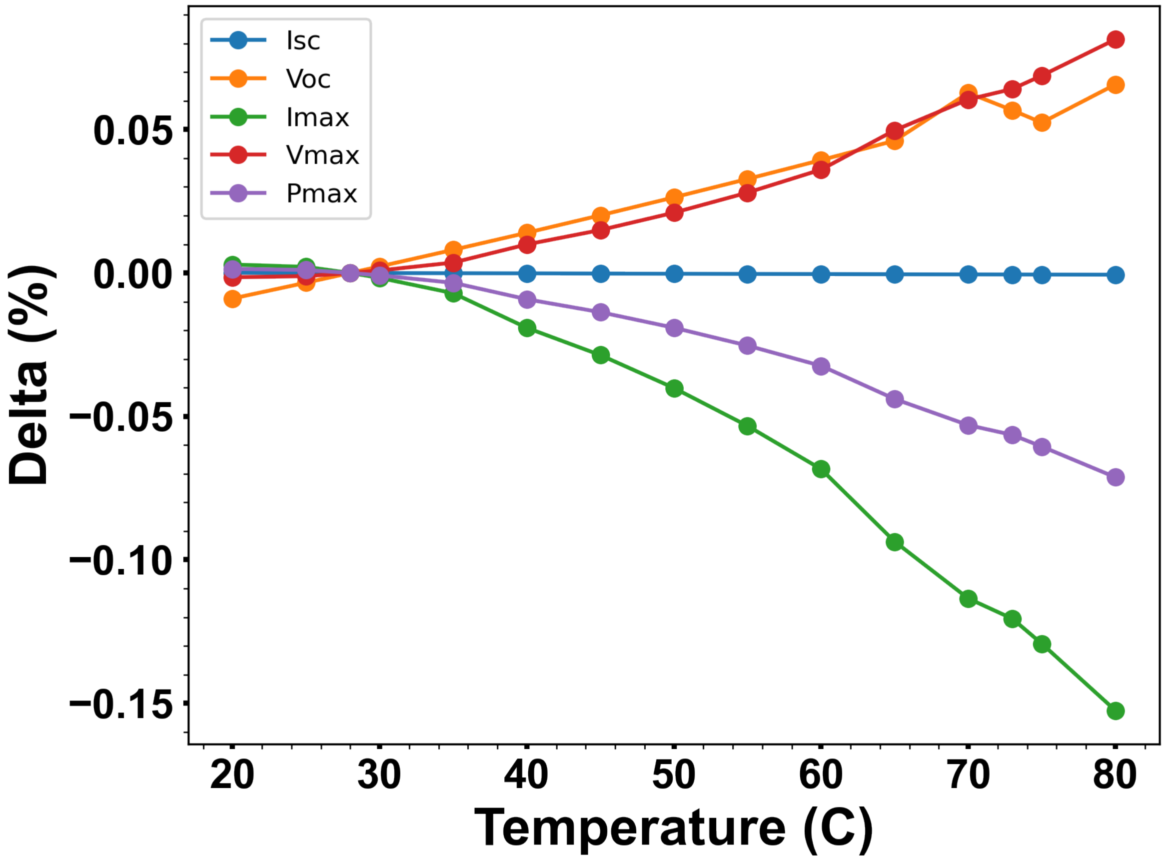



# *Validation of Temperature Correcting IV Curves*

- The extracted meta data ($I_{sc}$, $V_{oc}$, $I_{max}$, $V_{max}$, and $P_{max}$) from the temperature corrected IV curves (*meta*$_{IV\text{-}TC}$) is compared to the meta data at the starting temperature that has been temperature corrected only using temperature coefficients (*meta*$_{TC}$)

- *meta*$_{IV\text{-}TC}$ were extracted using ASTM E1036-15R19
  - *If $I_{sc}$ not within a certain voltage range of 0V is linear extrapolated to 0V*
  - *If $V_{oc}$ not within a certain current range of 0A is linearly extrapolated to 0A*
  - *$I_{max}$, $V_{max}$, and $P_{max}$ are found by taking a polynomial about the knee of the curve and the root is found.*

- *meta*$_{TC}$ is derived by taking the meta data at $T_{initial}$ corrected the meta data for the target temperature using only temperature coefficients

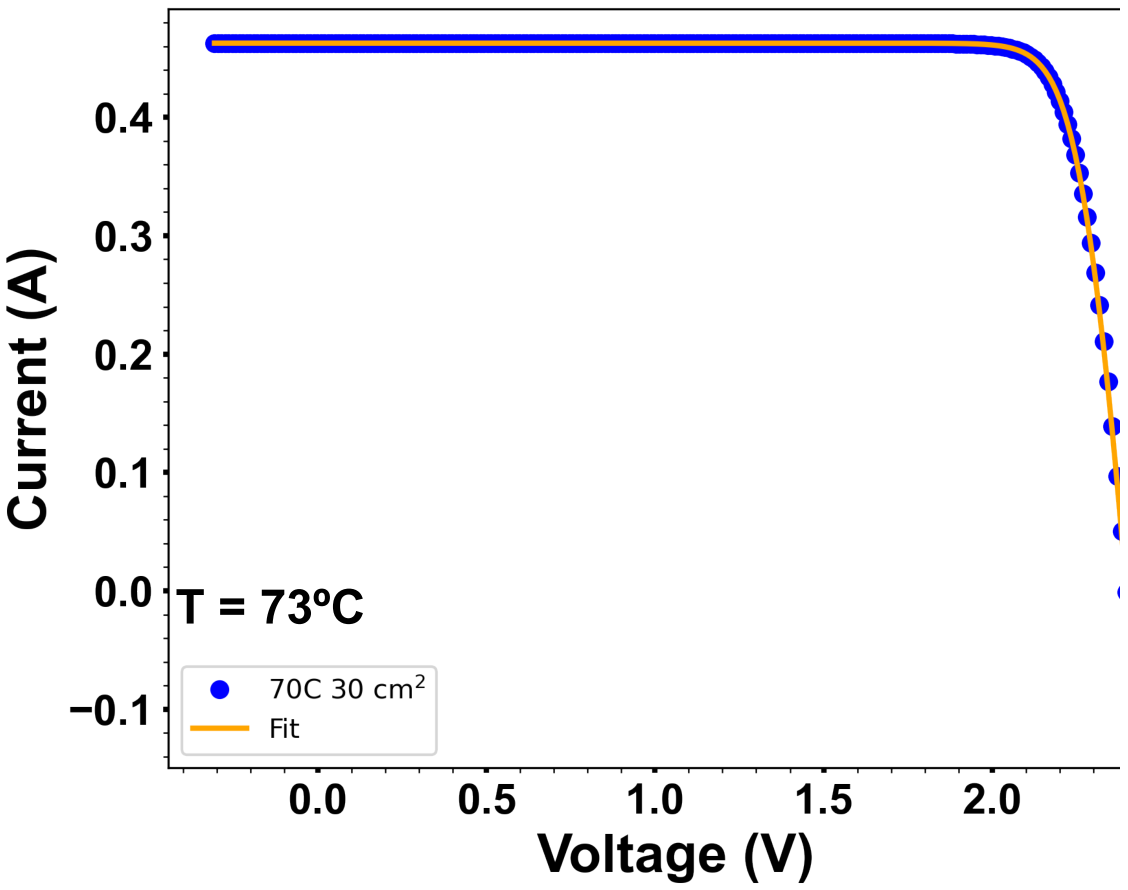



***Correction error is less than 0.06% from 20C -80C.***

# *Fit and Extract Single Diode Parameters*

## Results

- Single diode model was used as it allows for safe extrapolation and interpolation of an IV curve
  - *If subjunction IV data is available those should be used*
- The parameters can be used to numerically calculate the IV curve and as inputs into spice circuit model simulations that are used
- The five parameters needed for the single diode equation are the photocurrent ($I_{ph}$), saturation current ($I_0$), ideality factor ($n$), ), series resistance ($R_s$), and shunt resistance ($R_{sh}$)




| $I_{ph}$ (A) | $I_o$ (A) | n | $R_s$ Ω | $R_{sh}$ Ω | $r^2$ |
|---|---|---|---|---|---|
| 0.463 | 1.17e-19 | 2.15 | 0.17 | 1.33e5 | 0.999 |

# Fit and Extract Single Diode Parameters

## Methods

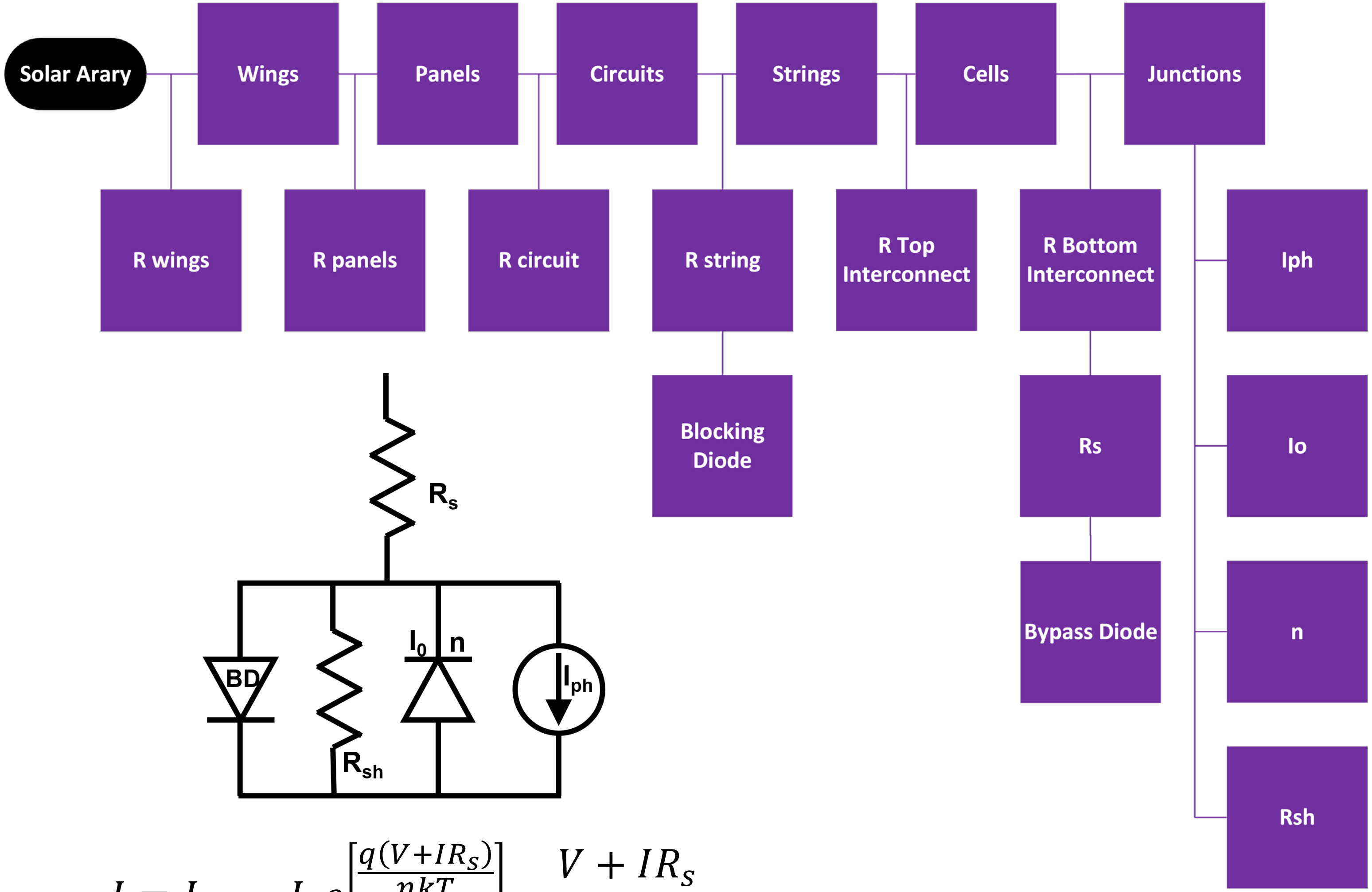
- We explored two methods to extract the parameters (there are over a 100)

1. Zhang Model (Journal of Applied Physics, 110, 064504 (2011)
   - *Only involves extracting three parameters (n, $R_s$, $R_{sh}$) and $I_{ph}$ and $I_0$, are calculated*
   - *The inputs are limited to the $I_{sc}$, $V_{oc}$, and a method to derive initial guesses for n, $R_s$, $R_{sh}$.*
   - *Produces values that are reasonable and trend in some direction and requires the user to have little knowledge in guessing the input*
   - *Achieves $r^2$ fits of 0.999*
   - *Easy to implement in python, matlab, etc.*

2. Toledo Model (Renewable Energy, 72, 2014, Pages 125-133)
   - *Non-iterative, analytical method that doesn't require fitting*
   - *The inputs include $I_{sc}$, $V_{oc}$, $I_{max}$, $V_{max}$, and one (I,V) point between $P_{max}$ and $V_{oc}$. The initial $R_{sh}$ is also needed and is determined by the slope of the IV curve near $I_{sc}$, but upon derivation of the 4 of the 5 parameters, $R_{sh}$ can be calculated*
   - *Produce $r^2$ fits of 0.98 to 0.999, but sometimes the 5 parameters do not correlate with one can visually interpret from the iv curve or what you would expect for radiation damage*
   - *Easy to implement in MS Excel*

# Build Array: psim

- The solar array model is built using psim
  - *psim is a python library that builds the solar cell array and generates a spice netlist that is then run using ngspice*
  - *Ngspice was chose as it is open source and free. The netlist generated can be run any spice simulator with little to no modification*
- The fundamental building element of the model is the diode equation and the solar cell IV curve




$$I = I_{ph} - I_o e^{\left[\frac{q(V+IR_s)}{nkT}\right]} - \frac{V+IR_s}{R_{sh}}$$

# *Include Uncertainty?*

- Loss factors for Current were grouped into 3 Groups
  - *Static*
    - Factors that are not affected by time varying components
    - These factors remain constant from the start of the mission
  - *Time Dependent*
    - Factors that change over time
    - Considered linear in the simplest case, but are more than likely nonlinear
  - *Uncertainties*
    - Uncertainties are treated as 1 sigma
- Totals
  - *This row shows how one would calculate total loss factors at end-of-life (EOL), but could also be applied at any given point in time*
  - *Static losses are multiplied to arrive at a total static lost factor*
  - *Time dependent total losses are also multiplied and the aphelion was used as the "worst case" EOL time dependent loss factor*
  - *Uncertainties are treated as uncorrelated, thereby we propagated the error by taking the square root of the sum of squares.*
    - Results in every solar cell in the array having different IV curves

| Loss Factor | Type of Loss | %Loss |
|---|---|---|
| **Static Loss** | **Installation Losses** | 0.98 |
| | **Off Pointing** | 0.995 |
| **Time Dependent** | **Earth Sun Distance** | 0.967-1.033 |
| | **Coverglass Darkening** | 1-0.95 |
| | **Adhesive Darkening** | 1-0.99 |
| | **Contamination** | 1-0.95 |
| | **Micrometeoroid** | 1-0.999 |
| **Uncertainties** | **Cell Measurements** | ±0.05 |
| | **Coverglass Darkening** | ±0.02 |
| | **Adhesive Darkening** | ±0.001 |
| | **Contamination** | ±0.05 |
| | **Micrometeoroid** | 0 |
| **Totals** | **Static (EOL)** | 0.975 |
| | **Time Dependent (EOL)** | 0.863 |
| | **Uncertainty** | 0.073 |
| | **Total Loss Factors (EOL)** | 0.841±0.073 |

# *Include Uncertainty? - Yes*

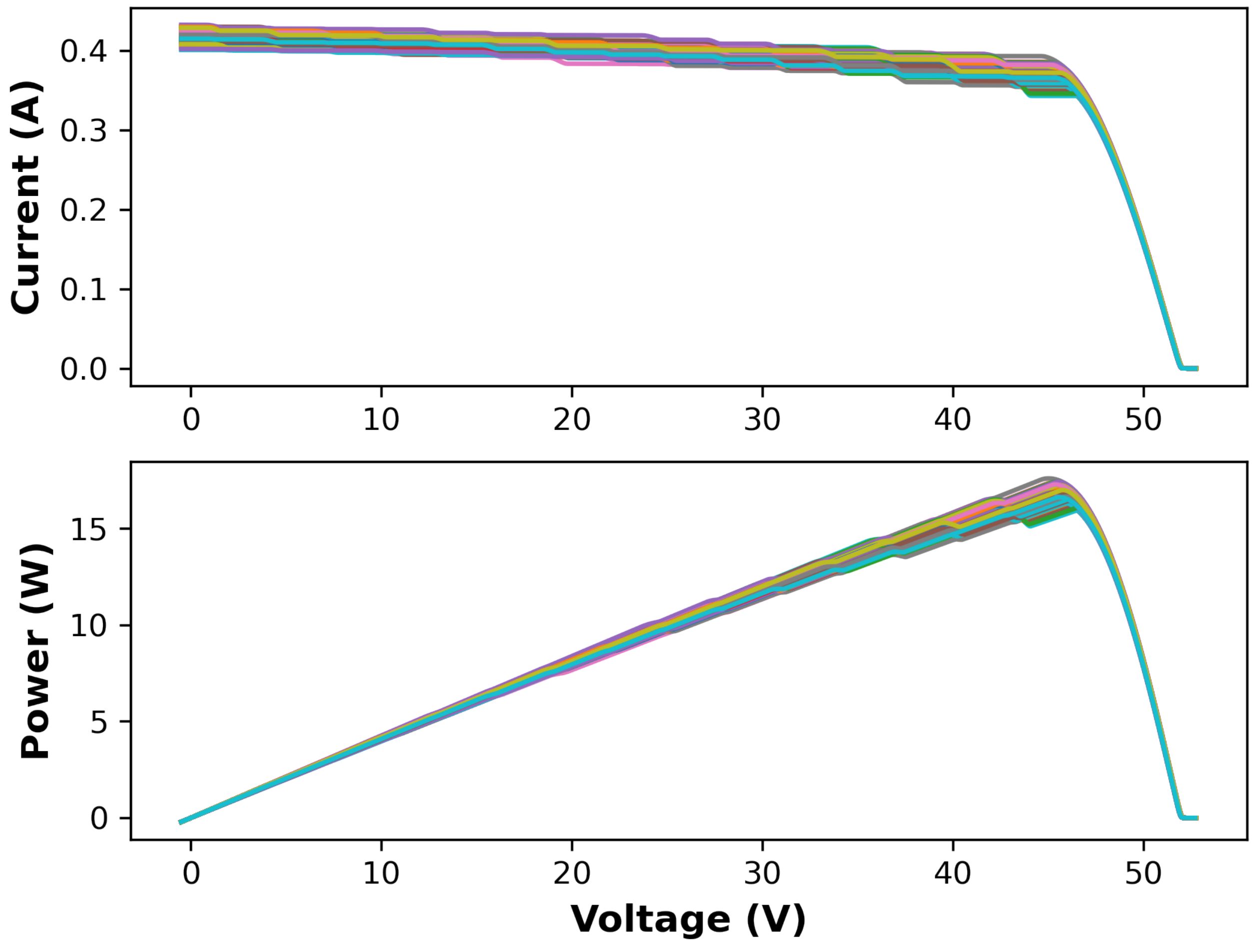
*Monte Carlo Simulation*

- The uncertainty derived in the previous chart is applied to $I_{ph}$ of each solar cell

- Using a random normal distribution each cell's $I_{ph}$ is adjusted resulting in a slightly different IV curve.
  - *Because the model is based on the diode equation, any increase or decrease in the current generate results in slightly higher and lower meta parameters.*
  - *The figure to the right represents 200 strings of 22 solar cells*

- To calculate the power of the array those 200 are simply added together.

- We repeat the generation of the plot to the right over and over to arrive at an average power



# *Result of MC Runs*

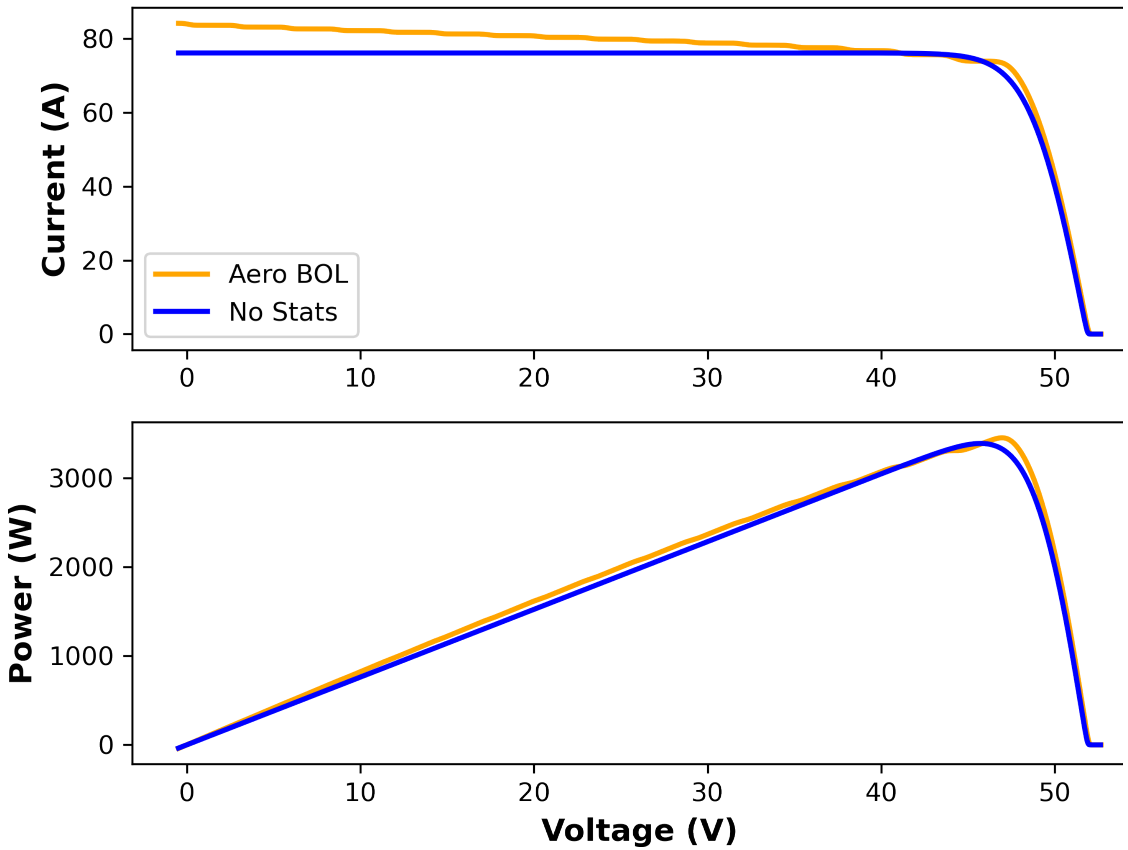
*Monte Carlo Simulation*

- Results presented are for 20 runs

- For the MC runs all the variability basically averages out over the array
  - *Randomly placing cells with photocurrents ranging over ±7% does not alter the power of the array very much as seen by the low standard deviations of the meta parameters*

- Slope of the IV curve is less square due to the variability being added to each string and the effect of the bypass diodes

- One effects use case of this MC method is randomizing failures of various components in an array




| | WC | MC Run | std |
|---|---|---|---|
| $I_{sc}$ (A) | 76.14 | 84.00 | 0.07 |
| $V_{oc}$ (V) | 52.38 | 52.62 | 0.06 |
| $I_{max}$ (A) | 74.06 | 73.61 | 0.16 |
| $V_{max}$ (V) | 45.72 | 46.84 | 0.02 |

# Conclusion

- We have developed a model and procedure for calculating array power that allows the incorporation of variability in performance and degradation factors at the cell level
- The model and method can be rooted in measured or simulated IV curves
- In our example we only randomized the loss in current but the variability in cell voltage can be adjusted using the saturation current
  - *Variability in the radiation environment can be applied using Ae9/Ap9 and solar cell radiation degradation models*
- Cells can be mapped to a real array or binned to arrive at the best array configuration
- We are working or open sourcing this to The Aerospace github page.
  - *Please suggest any features you would like!*