A Practical Framework for 3D Shade Modeling: Addressing the Tradeoff Between Precision and Performance

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***Abstract*— Accurately calculating shade geometry on solar photovoltaic (PV) modules in 3 dimensions (3D) is computationally demanding. Algorithms exist which can calculate the geometry of direct shade cast on PV modules with near perfect precision, but this precision comes at a cost. Memory utilization, computation time, and energy consumption are all increased if systems are modeled with maximum precision. Because of these trade-offs and the inherent uncertainty caused by differences between the physical plant and the digital model used to simulate it, the use of full-precision 3D models may not be justified.**

This paper explores one technique that may be applied to 3D shading models to greatly reduce the computational cost whilst maintaining accuracy. Specifically, the application of solar position binning at different bin widths is analyzed. Solar position binning reduces the total set of hourly (or sub-hourly) solar azimuth and zenith angles in a time-series simulation to a subset of predefined angles. Beam shade fractions are then explicitly calculated at those known spacings (bin widths) of solar position. Once the shade fractions are known at specific bin widths, solar positions that also appear in the time-series but lie between bin widths can be interpolated. We analyze the trade-offs associated with different bin widths of solar position and propose an optimized binning approach that balances accuracy requirements with computational performance. We then quantify the uncertainty of the interpolation technique at 4 different bin sizes. We demonstrate that some interpolation-based approximations have an acceptable amount of associated uncertainty given the practical implication of real world utility scale solar construction.

***Index terms*—Photovoltaics, Performance Modeling, 3D, Shade, PlantPredict**

I. Introduction

The energy yield of utility scale photovoltaic plants is often modeled by creating a virtual plant in 2 dimensions. This simplification is both logical and expedient if the physical plant being modeled is constructed on flat terrain. If, on the other hand, the physical plant being simulated is constructed on variable terrain, the assumption breaks down and a large underestimation of shading losses may occur. The error attributable to incorrectly modeling the geometry of the photovoltaic plant can represent a significant portion of the overall modeling error, and more concerningly, scales by some factor relative to the amount of terrain present at the site [1].

Unfortunately, a large barrier exists to simulating the energy yield of utility scale photovoltaic plants in 3D, namely the computational intensity of simulating a virtual power plant in 3 dimensions. One of the most computationally intense steps of this process is the calculation of shade geometry.

Today, there are 3 main methodologies for calculating 3D shade geometry on the front side: the polygon clipping method [2] employed by PlantPredict and PVSyst, the hemicube method [3] employed by SolarFarmer, and ray tracing methods, proposed by many companies and research groups, but not yet widely used in full scale models of utility scale PV power plants [4]. For the sake of brevity, only polygon clipping methods are discussed in this paper, though solar position binning and beam shade fraction interpolation could be similarly applied to other 3D shade geometry calculation algorithms.

Polygon clipping algorithms involve combining insights from the fields of projective and computational geometry. In short, polygons are projected into a plane orthogonal to the sun's rays and a boolean geometry algorithm is executed to determine how much shade is cast on other polygons that represent PV active surfaces. This operation is solved naively in $O(n^2)$ time and optimally in $O(n*\log(n))$ time. For solar performance engineers who may be unfamiliar with the study of time-complexity [5], in a simplified sense, it is a measure of how the number of calculations scale compared to the number of inputs for a given algorithm. The simplest, though slowest (sometimes called the naive approach) to solving the 3D shade problem across all objects in a scene is to select one object and then calculate the amount of shade cast on that object by every other object in the scene. The algorithm then moves onto the next object and repeats the process. This set of nested for loops is defined as $O(n^2)$ time. Because each time-step of a solar performance model must be solved as a separate scene, even if solving an individual scene takes only 1 second, a year long time-series of 8760 1 hour long time-steps will still take 2.4 hours to solve. A 1 year long time-series using 5 minute time-steps would take 29.2 hours to solve. Please note that the 1 second per time-step computation time is meant to be used as an easily understood example. Modern computers with efficient choice of algorithms can solve polygon clipping algorithms in the solar performance context in under 1 second per time-step.

Instead of solving every time-step, and therefore every permutation of sun apparent zenith and azimuth angles in the time-series, it is possible to solve a reduced set of sun angles and interpolate between them. The term "binning" is used in this paper to describe how the full set of possible sun angles is sampled. A coarse bin refers to a binning strategy which creates wide gaps between calculated points. A fine bin, in contrast, simulates an increased number of calculated points and therefore reduces the distance on average between calculated and interpolated points.

In this paper we show that interpolation methods allow us to achieve acceptable levels of accuracy at a faster speed, improving the feasibility of 3D simulation methods in optimization use cases as well as reducing the carbon intensity of these 3D calculations without compromising the simulation results. We compare the uncertainty created in the performance model due to bin width selection to certain factors inherent to the development of utility scale photovoltaic plants.

II. Methods

Using PlantPredict's 3 dimensional shade calculation engine, 3 different binning strategies were attempted. The first binning strategy involves no binning. Each time-step is evaluated independently and no strategy is used to interpolate between similar sun positions within the simulation run. This case represents the base case for this analysis and computes 100% of the time-steps in the broader energy model.

The second strategy involves binning apparent zenith and azimuth solar positions into 1 degree bins. This reduces the number of time-steps that need to be evaluated to approximately 25%, if the simulation run happens to be at an hourly interval. The third strategy involves binning apparent zenith into 10 degree bins and azimuth into 20 degree bins. This reduces the number of time-steps that need to be evaluated to approximately 5%, if the simulation run happens to be at an hourly interval.

In order to determine the error metrics for each binning strategy, a virtual 13 MWp power plant was created in the desert South-West portion of the United States. The system uses a mono-facial crystalline silicon module, a central inverter, a 40% ground coverage ratio (GCR) and has a 1.3 DC:AC ratio. A standard ground coverage ratio (GCR) based backtracking strategy was applied in order to simulate the worst case scenario in shading losses.

This underlying power plant design was then copied 4 times across increasingly complex terrain scenarios. In order to create the different terrain scenarios, the underlying surface elevations of the plant were digitally manipulated to create variable slopes which could be built upon with commercially available tracker technologies. All elements of the power plant design were kept constant across the 4 terrain scenarios, but the tracker geometry was allowed to vary depending on the underlying terrain.

Once these 4 digital plants were created, they were modeled in PlantPredict version 12 using 3 separate binning strategies in order to create a 4 x 3 table of energy predictions.

A. *Dimension 1: Terrain*

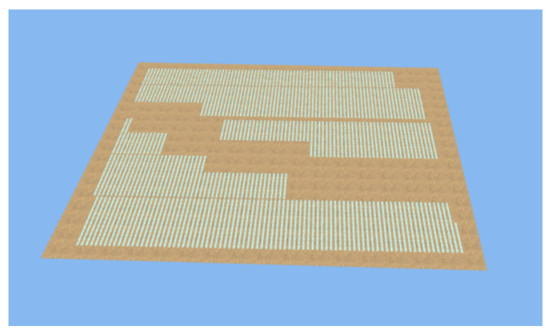

Figure 1: The PV System on Flat Terrain

The first case "Flat" assumes standard trackers on entirely flat terrain. The flat case differs from a hypothetical two-dimensional shade scene in that the shade engine takes into account shading edge effects for trackers that are not situated within an infinite set of adjacent trackers. Because two dimensional approximations do not take into account edge effects, they will slightly over-estimate shading compared to 3 dimensional calculations.

In the context of this study, standard trackers are defined as trackers which cannot articulate in the north-south, torque-tube axis direction. In contrast, terrain-following trackers can have some articulation points in the torque-tube direction, meaning there may be one or more points along the torque-tube axis in which the torque-tube changes angle. These points in the model correspond with the points in which the torque-tube comes into contact with a tracker pile. Terrain-following trackers are modeled in this study as piece-wise linear with connections occurring at each pile location.

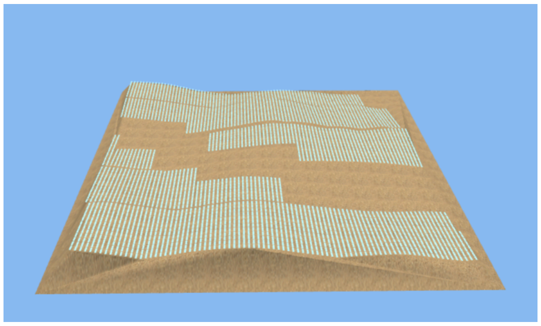

Figure 2: The PV System on Mild Terrain

The “Mild” case also assumes standard trackers, but the underlying terrain is varied in such a way that trackers are at some points out of direct alignment with adjacent trackers. Trackers in this scenario may have different torque-tube axis tilt angles from their neighbor trackers, but do not articulate. The change in angle from pile to pile in the east-west direction is 8.2 degrees on average. The maximum change in angle from pile to pile within a tracker is limited to 0 degrees. The maximum slope in the torque-tube axis direction is limited to 8.5 degrees.

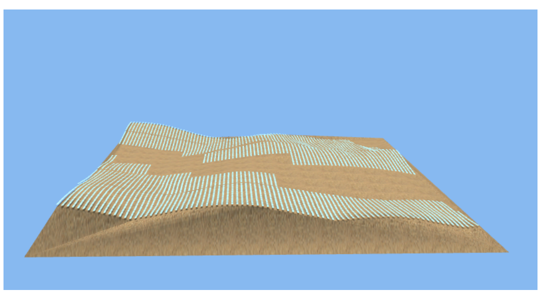

Figure 3: The PV System on Medium Terrain

The “Medium” case assumes terrain following trackers on similar terrain to the “Mild” case. The change in angle from pile to pile in the east-west direction is 10.8 degrees on average. The maximum change in angle from pile to pile within a tracker is limited to 1.5 degrees. The maximum slope in the torque-tube axis direction is limited to 8.5 degrees.

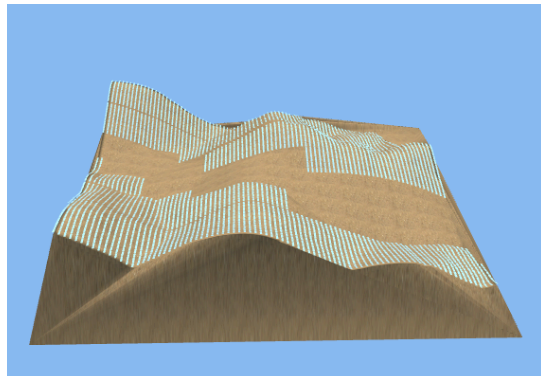

Figure 4: The PV System on Complex Terrain

The “Complex” case assumes terrain following trackers. The change in angle from pile to pile in the east-west direction is 23.7 degrees on average. The maximum change in angle from pile to pile within a tracker is limited to 14.6 degrees. The maximum slope in the torque-tube axis direction is limited to 20.5 degrees. Because of these extreme terrain slopes, this case is meant to be representative of the worst possible terrain that can be constructed given the limitations of the most terrain adaptable, commercially available horizontal single-axis tracking systems.

B. Dimension 2: Bin Size of Interpolation

Regarding the second dimension over which results were generated, the interpolation strategy utilized by PlantPredict's shade engine is likely unfamiliar to users familiar with interpolation calculated by other photovoltaic performance modeling software. Instead of calculating a regularly spaced grid of sun angles and tracker rotation angles at each bin level, a set of representative time-steps is chosen from the time-series data set. This reduces the overall number of calculations required, removes the requirement for the direct shade fraction calculation to be done in two steps, and allows users to define custom tracker angles without also having to provide custom angles for the 2d regularly spaced grid. Representative time-steps are chosen to as closely match a regularly spaced grid as possible.

III. Results

The near shading losses calculated by PlantPredict include shading on the direct, diffuse and reflection onto the front-side components of irradiance. The flat scenario has no direct shading due to the fact that the system uses a standard GCR-based backtracking algorithm intended for 2D terrain. This means that all of the near shading present in the flat scenario can be attributed to diffuse shading, which is calculated by 2D view factor. The shading that occurs on the irradiance that is reflected onto the front side is a small portion of the overall energy and is effectively ignored for the purposes of this study.

Table 1 displays the amount of energy lost for each system when modified to fit a given terrain scenario and a given binning strategy. The loss percentage does not include losses due to electrical mismatch.

TABLE 1
ENERGY LOST DUE TO NEAR SHADING EXCLUDING MISMATCH [%]

Terrain	No Bin	1/1	10/20
Flat	2.08	2.08	2.08
Mild	4.47	4.48	4.42
Medium	5.46	5.48	5.42
Complex	10.50	10.52	10.23

In Table 2 and 3, error metrics for direct shade fraction between the base case scenario, which employed no sun angle binning, and the test scenarios that incorporated varying degrees of sun-angle binning are shown. Higher R-squared values indicate a stronger correspondence between the base case and the test scenario, suggesting that sun-angle is a good predictor of direct shade fraction, even if the model used to determine shade fraction is a simple linear interpolation. The error metrics for direct shade fraction do not directly correspond to error metrics in energy since different time-steps have different ratios of beam and sky-diffuse irradiance, as well as different amounts of plane of array irradiance.

TABLE 2
1/1 BIN, SHADE FRACTION ERROR METRICS

Terrain	MBE [%]	RMSE [%]	R^2
Flat	0.0	0.0	1.0
Mild	0.00004	0.0026	0.99997
Medium	0.000002	0.0025	0.99997
Complex	-0.0001	0.0024	0.99997

TABLE 3
10/20 BIN, SHADE FRACTION ERROR METRICS

Terrain	MBE [%]	RMSE [%]	R^2
Flat	0.0	0.0	1.0
Mild	-0.0081	0.0597	0.985
Medium	-0.0063	0.0341	0.995
Complex	-0.0035	-0.0240	0.997

IV. CONCLUSION

A few major conclusions can be drawn from the study. First, a sun angle binning strategy of 1 degree of apparent zenith and 1 degree of azimuth is more than sufficient for accurately calculating direct shading losses in utility scale solar power plants. This conclusion is robust across increasing terrain and tracker design complexity. Given how closely the results for a 1 degree, 1 degree bin width approximate the full time-series of results, photovoltaic system modeling professionals should feel comfortable in all cases choosing the more expedient method.

Second, it can be noted that a binning strategy of 10 degrees of zenith and 20 degrees of azimuth gives a good estimate of total energy lost for flat, mild and medium terrain scenarios, but can introduce an error of up to 0.3% in annual energy if used in complex terrain scenarios. In the utility scale context, this larger bin size is likely appropriate for most scenarios. In contrast, it may be an in-appropriate simplification if the site shade scene is dominated by thin objects such as roof plumbing pipes in a context such as residential solar.

A surprising conclusion that can be drawn from these results is that R^2 of beam shading fraction on its own is not a good enough metric to determine how close the resulting energy will be at the effective plane of array level. If, for example, most of the agreement between the interpolated and calculated time-steps occurs during times of high diffuse fraction or at low irradiance then the effect of a high R^2 can be nullified.

It is also clear that the uncertainty due to the underlying terrain greatly exceeds the uncertainty due to the binning strategy. The uncertainty due to differences in the digital plant and digital terrain relative to the as-built physical plant should be weighed when selecting a bin width for interpolation.

A few things that could be done to further this line of research include: attempting a bi-linear interpolation strategy across both azimuth and zenith instead of linearly interpolating over zenith, attempting other bin widths such as 5 degrees of zenith and 10 degrees of azimuth, and including shading electrical effect losses.

This work has examined a range of terrain scenarios for horizontal single axis trackers which spans the entire range of what is currently claimed by tracker manufacturer to be build-able. It has been demonstrated that interpolation is both an expedient and accurate way to model the effects of 3D objects on beam irradiance attenuation, though due to the infinite number of possible 3D scene, the ultimate acceptance criteria of which bin width to use remains at the discretion of the modeler.

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