IRIS Photovoltaic Solar Project (85JP 8ME, LCC)

REFLECTIVITY ANALYSIS

REVISION INDEX

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Contents

1 Introduction

This document analyzes the risk of sun reflectivity due to a series of flat photovoltaic systems (PV) being developed by 85JP 8ME, LLC in the Imperial County. The project consists of a series of farm lands as shown in Fig. 1 below. The location is in relatively close proximity to a series of public roads, including but not limited to Hwy 98 in the South limit of some of the Project parcels.

Reflectivity events due to the presence of PV systems might have the possibility of affecting land traffic visibility if reflected sun light beam intersects the approaching vehicles' paths.

Fig 1.- Location of PV Project and public roads

To evaluate the risk of direct sun light reflection events a mathematical (geometric) model has been developed. The model predicts which times of the year there is a possibility for approaching vehicles to suffer direct reflection from the PV systems.

2 Definitions

The following definitions and descriptions are essential to understanding the methodology and results of this study:

Photovoltaic System – A PV system consist of a series of flat photovoltaic modules mounted on any of the following supporting structure types:

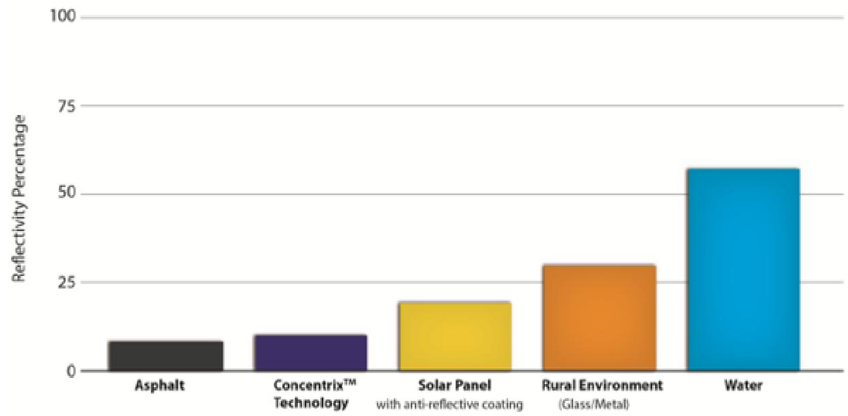
- Fix tilt structures
- Single axis tracker structures
- Two axis tracker structures

Depending on the supporting structure type, the modules shall be fix-tilt or moving towards the sun with appropriate solar tracker structures. A Varying orientation provides the PV modules a higher sun exposure.

By nature, PV panels are designed to absorb as much of the solar spectrum as possible in order to convert sunlight to electricity and are furnished with anti-reflective coating for that purpose. Reflectivity levels of solar panels are decisively lower than standard glass or galvanized steel, and should not pose a reflectance hazard to viewers. The graph in Fig. 2 below relates the reflectivity properties of solar modules as a function of the incidence angle, and compares them with other common reflecting surfaces in an airport related environment.

Reflected light from standard PV modules' surface is between 10% - 20% of the incident radiation, which is as low as free water surfaces; while galvanized steel (used in industrial roofs) is between 40% and 90%. It should also be noted that high incidence angles are always related to low sun elevation angles (i.e, the sun beams are close to being tangent to the reflecting surface) and, in this case, the intensity of incident light is much lower would be delivered at say noon time.

FIGURE 11 COMPARATIVE REFLECTIVE ANALYSIS



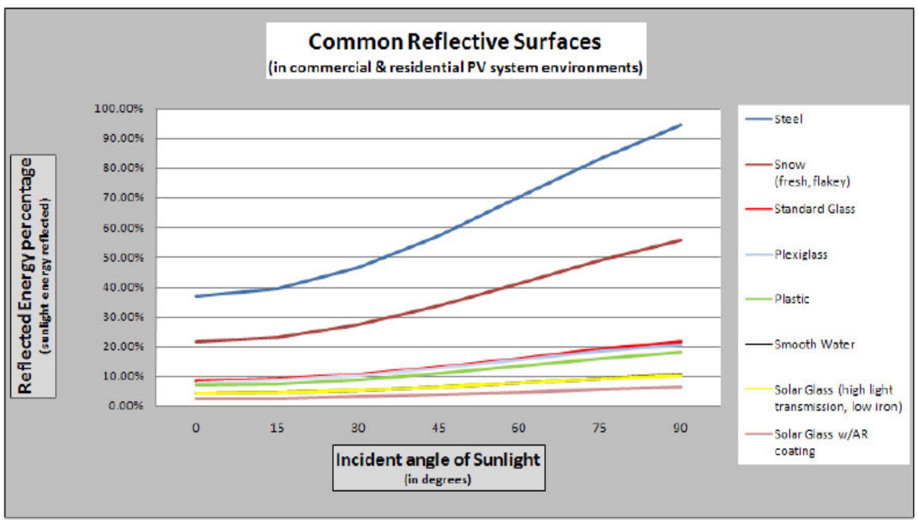


Fig. 2 – Reflectivity of several materials

Glint – Also known as a specular reflection, produced by direct reflection of the sun beam in the surface of the CPV solar module. This is the potential source of the visual/reflectivity issues regarding viewer distraction. Glint is highly directional, since its origin is purely reflective.

Glare – Is a continuous source of brightness, relative to diffused light. This is not a direct reflection of the sun, but rather a reflection of the bright sky around the sun disk. Technically this is described as the reflection of the circumsolar diffuse component. Glare is significantly less intense than glint and has negligible effects. As Glare is the reflection of diffuse irradiance, it is not a direct reflection of the sun. Other glare sources in nature (often called Albedo reflectance) are much more intense that glare from PV modules. For instance an agricultural environment or free water surfaces have higher glare effect than PV modules.

Key View Point (KVP) – KVPs are viewpoints used in the glint and glare study. In this analysis, a KVP can be any point located in the public roads around the PV Project.

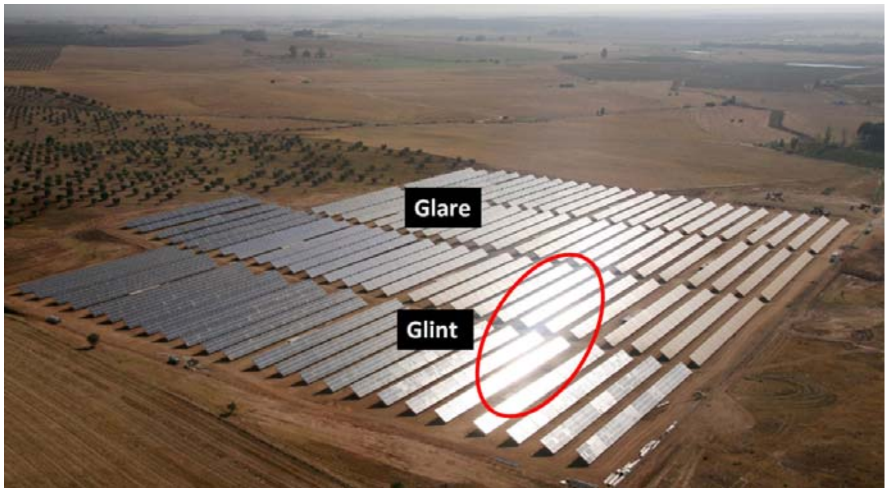


Fig 4 .- Glint and Glare identification by a PV installation

3 Mathematical analysis

3.1 Reference coordinate system

Solar reflection from flat surfaces is a mathematical problem that can be solved by means of 3D geometry concepts. In order to properly relate sun position, PV modules position and orientation, and the KVP location; it is necessary to define a global coordinate system to which the previous position and orientation will be referenced.

In this analysis, the 3D Cartesian coordinate system is defined as follows:

Positive X-Axis	Pointing South
Positive Y-Axis	Pointing East
Positive Z-Axis	Pointing upwards

The origin of the coordinate system is chosen at the South-West corner of the future PV plant sections, as shown in Fig. 5 below:

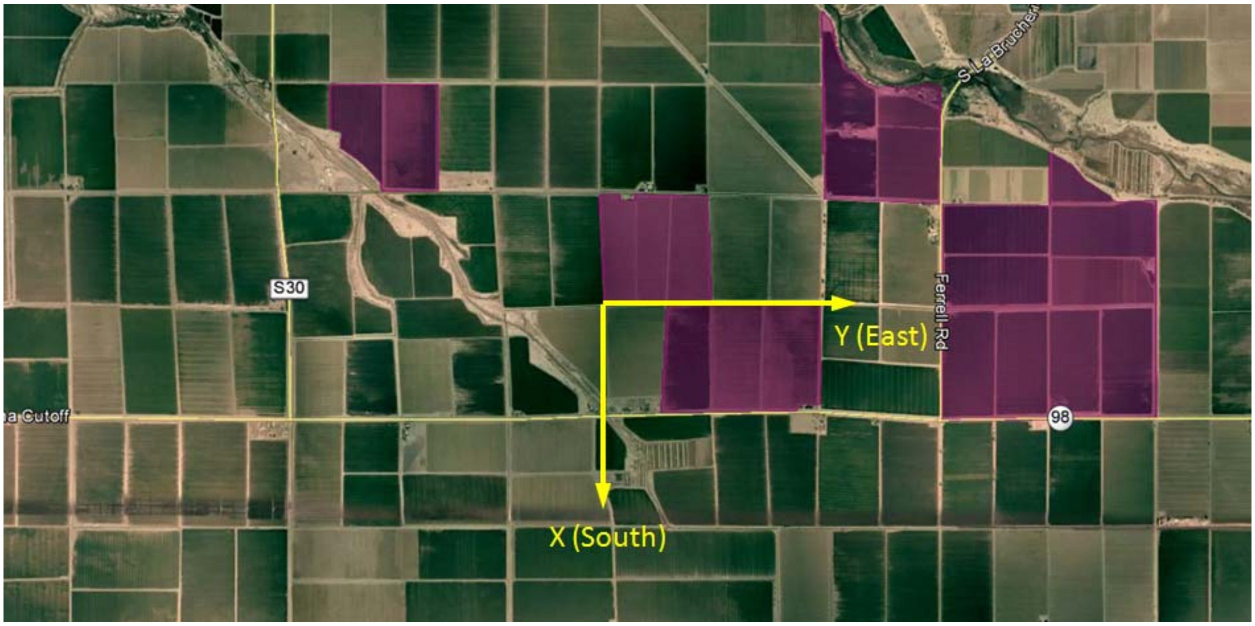


Fig 5 .- Reference coordinate system

Because of the square shape of the parcels (and wherever there are public roads around them), the results will be presented for the indicated parcel attached to the reference coordinate axis if Fig. 5. All results will be applicable to the rest of the parcels. The size of the parcel is assumed to be square and 2,600 ft x 2,600 ft side.

3.2 Sun position

Instantaneous sun position is defined by two angular (spherical) coordinates. These angles are Azimuth (φ) and Elevation (θ). Azimuth is the deviation of sun's horizontal projection from South, while elevation is the angle between the horizontal plane and sun's position. The following graphs illustrates the above definitions, and criteria for positive values:

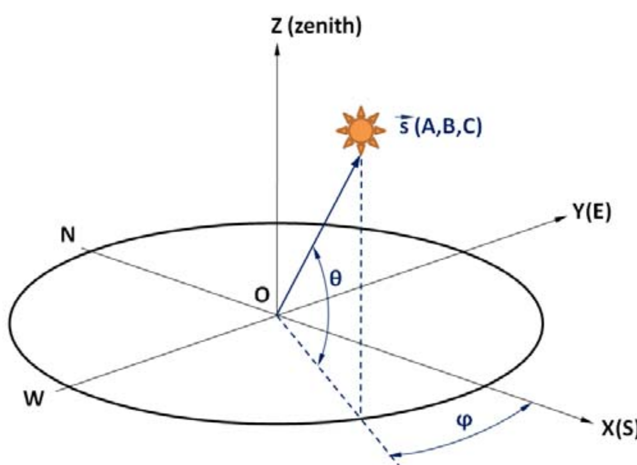


Fig 6.- Sun position coordinates

Sun position can be also defined by a unit-length pointing vector s = (A, B, C). Cartesian coordinates of the sun position vector are written in terms of the azimuth and elevation angles as follows:

$$A = \cos\theta\ \cos\varphi$$
$$B = -\cos\theta\ \sin\varphi$$
$$C = \sin\theta$$

Azimuth and elevation angular coordinates (φ, θ) are both function of:

- Earth latitude (L) at the origin
- Time: Day of the year (i) and hour of the day (H)

and can be calculated as per the following equations:
Earth declination:

$$D = 23.45\ \sin(0.986[284 + i])$$

Azimuth and elevation angles:

$$\sin\theta = \sin D \sin L + \cos D \cos L \cos H$$
$$\cos\varphi = \frac{\sin D\ \cos L - \cos D \sin L \cos H}{\cos\theta}$$

In the above expressions the day of the year (i) is following a Julian day convention (January, 1st is i=1; February, 1st is i = 32,… until i =365). The hour of the day (H) is referred to noon time (12:00 is H = 0; 10:00 is H = -2; 14:00 is H = +2; … etc).

As an example, the calculated values for azimuth and elevation angles for the equinox (March, 21st, i = 80) are plotted in function of the hour of the day in Fig. 7.

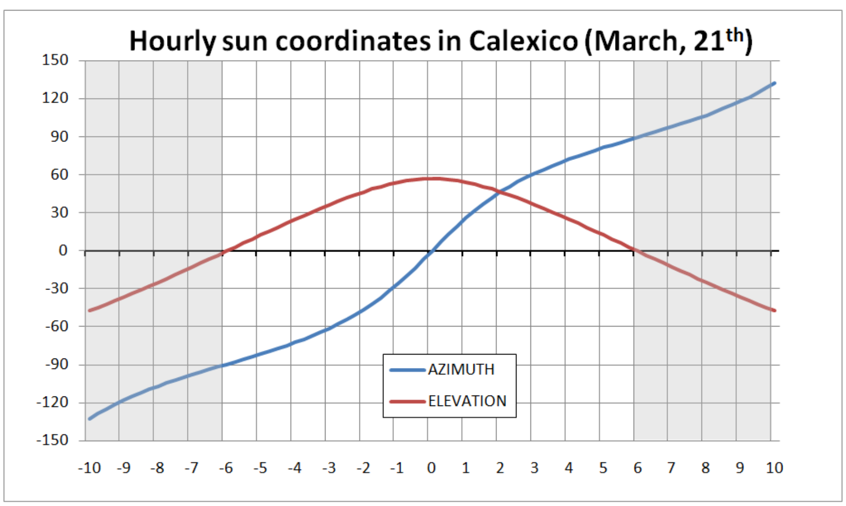


Fig 7.- Sun position coordinates in function of hour of the day

Negative values of the elevation angle means night time (the sun is below the horizon). In the above example the daylight period is 12 hours and the azimuth at sunrise is -90° (pure East), as expected for the equinox. Maximum elevation angle (at noon) is 56.88° for this latitude and particular day.

For the purpose of geometric calculations later in this report, the relevant results are the Cartesian coordinates of the sun position vector (A, B, C). For the sample day above, these are plotted in Fig. 8:

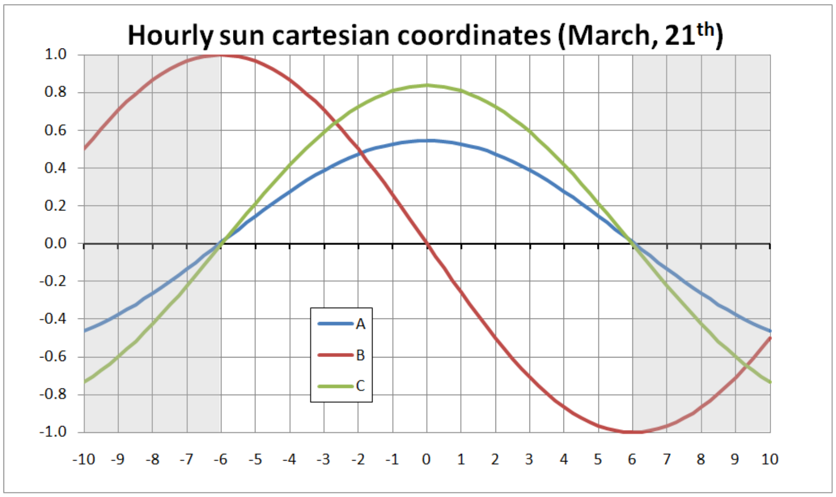


Fig 8.- Sun position vector Cartesian coordinates in function of hour of the day

3.3 Reflection equations for fixed tilt systems

PV modules are considered reflecting planes located at the origin of the coordinate system (O). A plane is geometrically defined by its perpendicular (normal) unit vector [n]. Notation for Cartesian coordinates of this fixed vector is n = (Ap, Bp, Cp). From the PV plant optimum design, the PV modules are facing South with a tilt angle of 25°, as shown in Fig. 9.

Then the fixed coordinates of this normal vector for the reflecting plane are given by:

$$A_p = \sin 25° = 0.42262$$
$$B_p = 0$$
$$C_p = \cos 25° = 0.90630$$

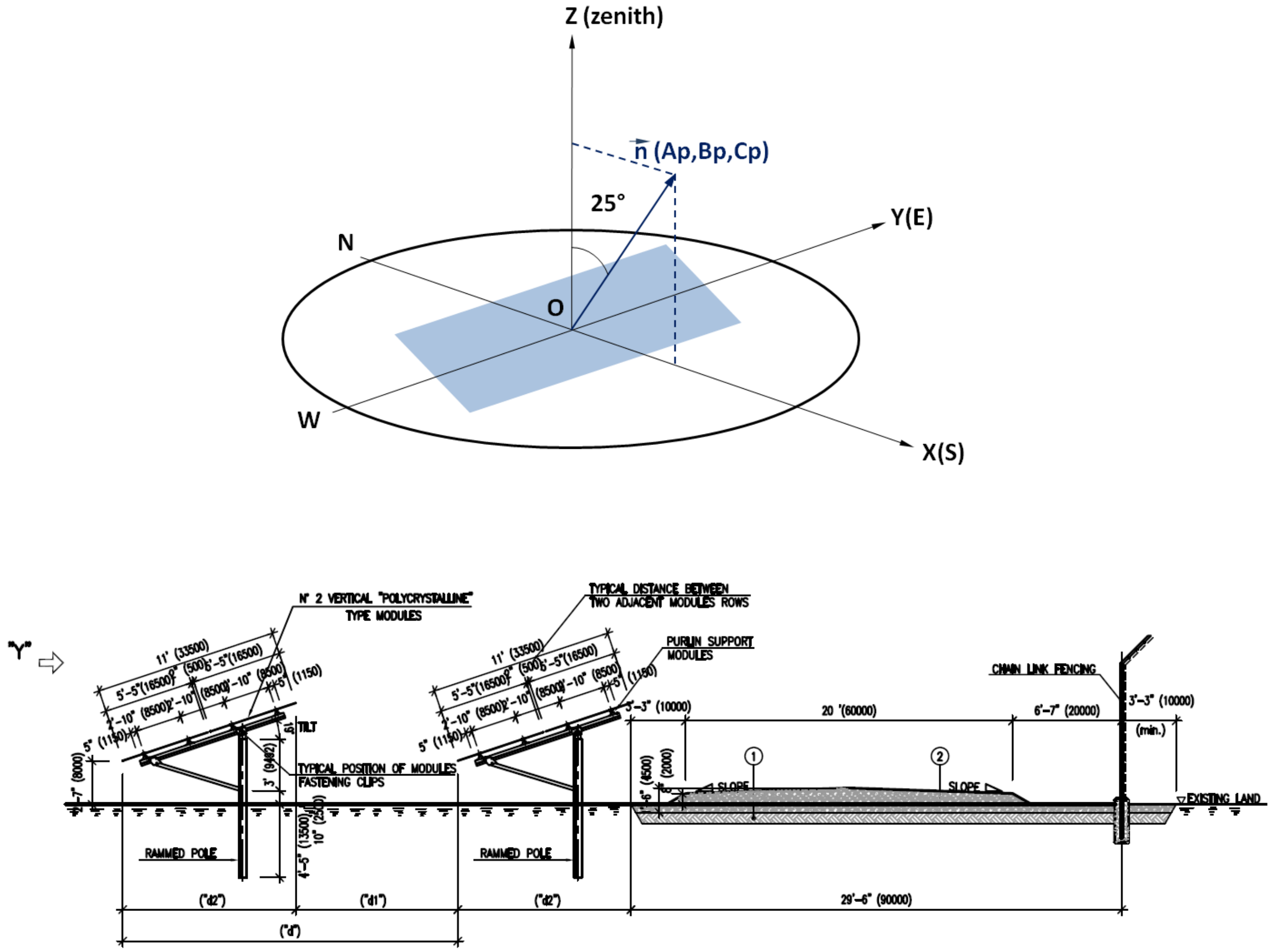
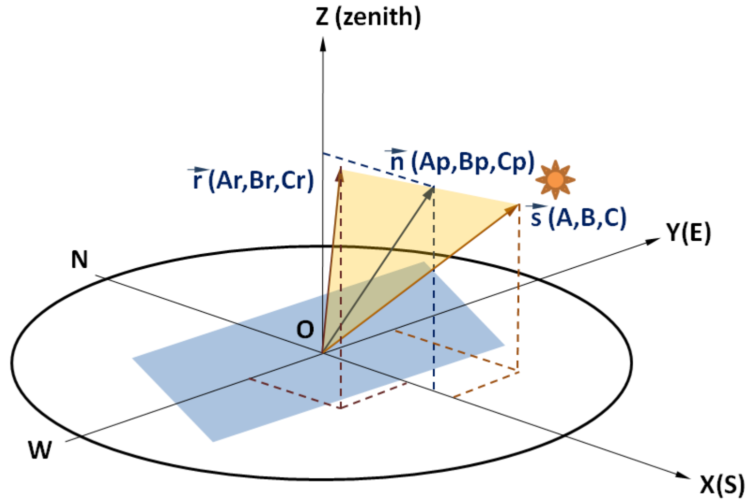


Fig 9.- Reflecting surfaces – Coordinates and typical PV design

Reflection of sun beams by a given surface can be calculated once the direction of the incident beam and plane orientation is known.

Instantaneous solar beam direction vector s = (A, B, C) and reflecting plane normal vector n = (Ap, Bp, Cp) intersects at the origin, and both defines a new plane in the space. From reflectivity laws, the reflected beam vector r = (Ar, Br, Cr) will be contained in this plane and symmetric to the incident beam with respect to the reflecting surface vector, as shown in the next figures:



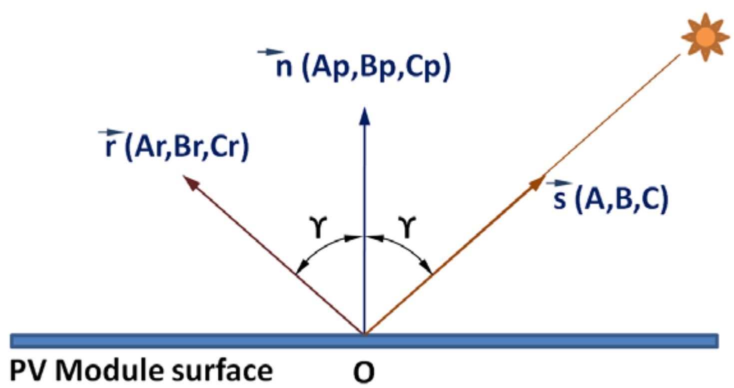


Fig 10.- Reflecting surfaces – Notation for reflected beam vector

A relevant variable in this figure is the incidence angle [ϒ], which measures the angle between the incident sun beam vector and the surface normal. No reflection can occur when the incidence angle is equal or larger than 90°. This situation will occur whenever the sun is behind the PV modules surface. The incidence angle can be calculated as per the dot product of unit vectors [s] and [n]:

$$\cos \gamma = \vec{s}\ \vec{n} = A\,A_p + B\,B_p + C\,C_p$$

The symmetric-reflected vector [r] is calculated as

$$\vec{r} = 2\ \cos \gamma\, \vec{n} - \vec{s}$$

and its Cartesian coordinates given by:

$$A_r = 2\ \cos \gamma\, A_p - A$$
$$B_r = 2\ \cos \gamma\, B_p - B$$
$$C_r = 2\ \cos \gamma\, C_p - C$$

For example, for the equinox day chosen the results for (Ar, Br, Cr) are plotted below in function of the hour of the day. Incidence angle cosine also included.

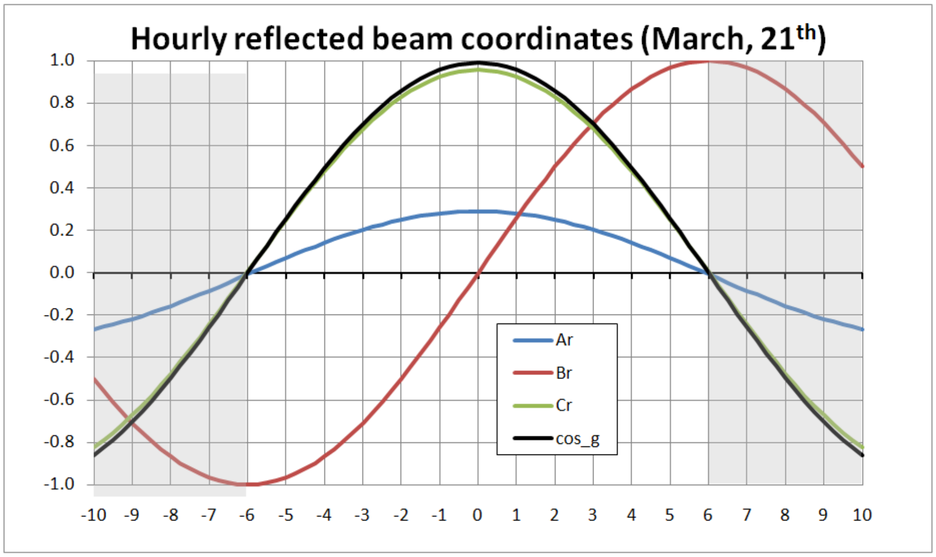


Fig 11.- Reflected vector coordinates and incidence angle

3.4 Reflection equations for horizontal axis trackers

Tracker systems are mechanical devices that continuously change the PV modules orientation with sun position, so to obtain the maximum irradiance at any time during the day. In particular, the horizontal axis trackers are oriented in North-South direction, so the modules attached to the horizontal rotating axis are inclined towards East during sunrise and are rotated towards West as the earth rotates.

Vector coordinates for the reflected beam are the same as described in paragraph 3.3, but in this case the vector perpendicular to the modules is not constant along the day, but rotating with the horizontal tracker axis. Target is to keep the incidence angle as close a zero as possible.

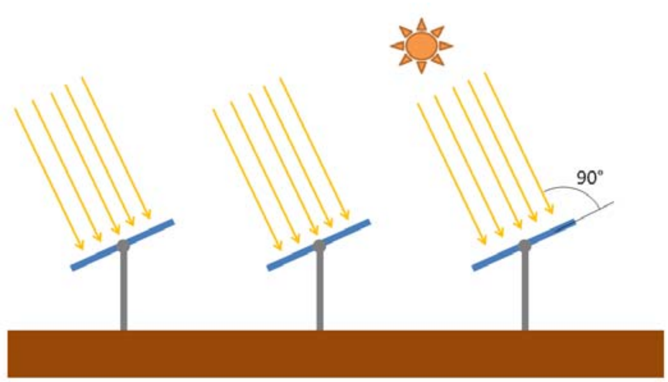


Fig 12.- Tracking angle of horizontal axis trackers

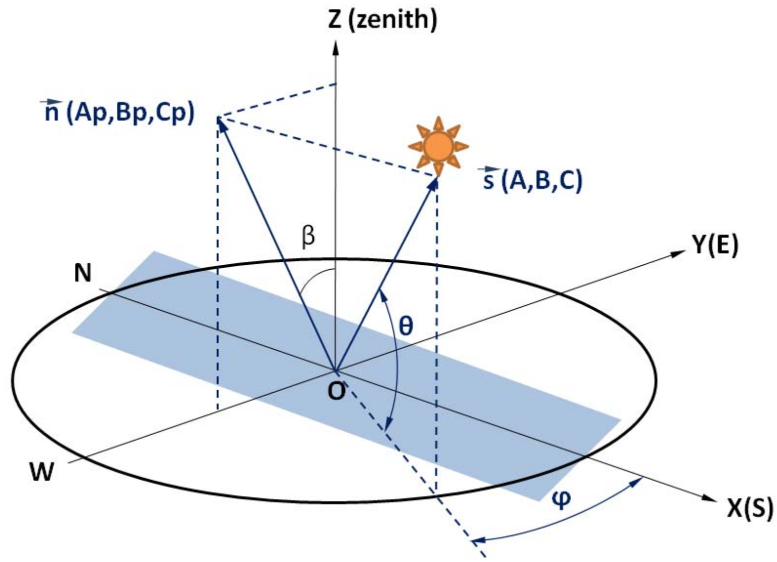


Fig 13.- Normal vector to PV modules in an horizontal axis tracker

Given the instantaneous rotation of the tracker as an angle (β), the normal vector n=(Ap, Bp, Cp) perpendicular to the plane of the modules is

$$A_p = 0$$
$$B_p = -\sin\beta$$
$$C_p = \cos\beta$$

The objective is to track for the minimum incidence angle (γ). This will occur also if the cosine of the incidence angle (γ) is a maximum:

$$\cos\gamma = \vec{s}\ \vec{n} = A\ A_p + B\ B_p + C\ C_p$$

this can be written as

$$\cos\gamma = -B\sin\beta + C\cos\beta$$

The minimum incidence angle occurs when

$$\frac{d\ (\cos\gamma)}{d\beta} = -B\cos\beta - C\sin\beta = 0 \qquad \tan\beta = -\frac{B}{C}$$

Which describes the rotation angle of the tracker in function of sun position, and hence the coordinates for the vector perpendicular to the plane of the PV modules.

3.4.1 Backtracking

At low sun elevation angles (i.e., sunrise and sunset), the trackers would be fully deployed and mutual shading between successive rows of modules will occur. To avoid this situation, the tracking control system has the so called backtracking algorithm, which defines the tracker rotation angle so to avoid this mutual shading. When the backtracking is active, the tracker will not rotate to follow the sun path, but to avoid mutual shading between rows. This occurs every day early in the morning and late in the evening, and depends on the PV plant geometry, day of the year and latitude.

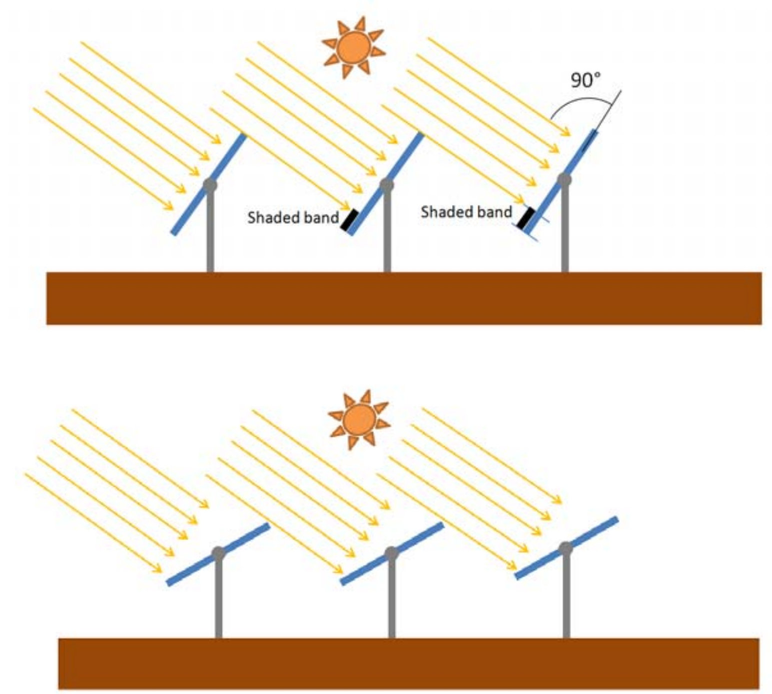


Fig 14.- Above: Mutual shading without backtracking.
Below: Backtrackin corrected incidence angle to avoid mutual shading

The tracker angle when the backtracking is active is given by the following equation:

$$\tan\theta = \frac{L\ sin\beta}{p - Lcos\beta}$$

Where [L] is the length of the modules (6.46 ft) and [p] is the pitch between tracker rows (19.6 ft). Maximum tracker angle is ±45° for mechanical and constructive reasons.

Fig. 15 shows the tracker angle, together with sun elevation angle for a sample day (March, 21st).

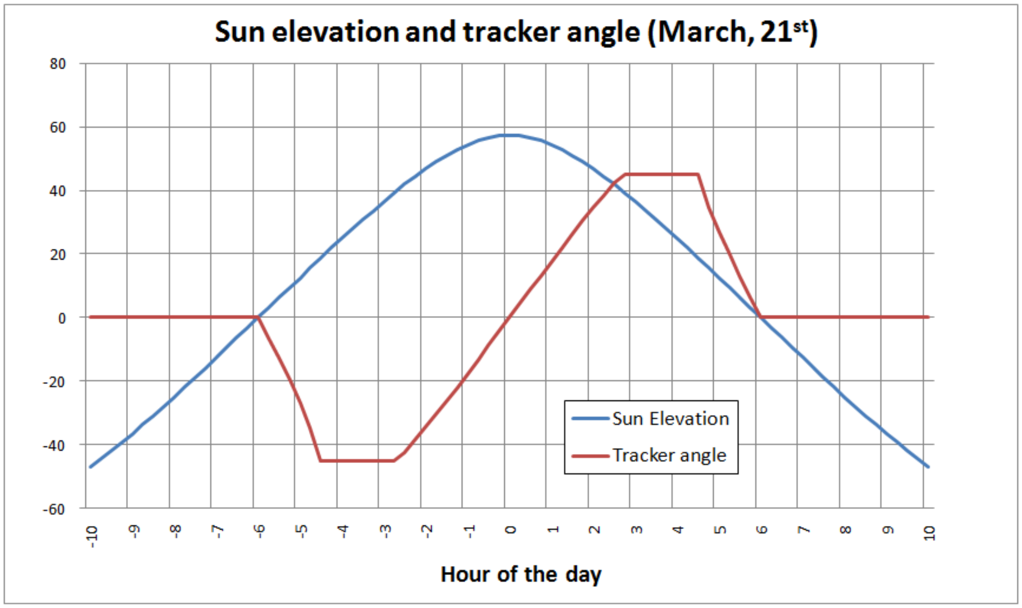


Fig 15.- Tracker angle on a sample day

Cartesian coordinates of the reflected beam, and incidence angle are shown in Fig. 16,

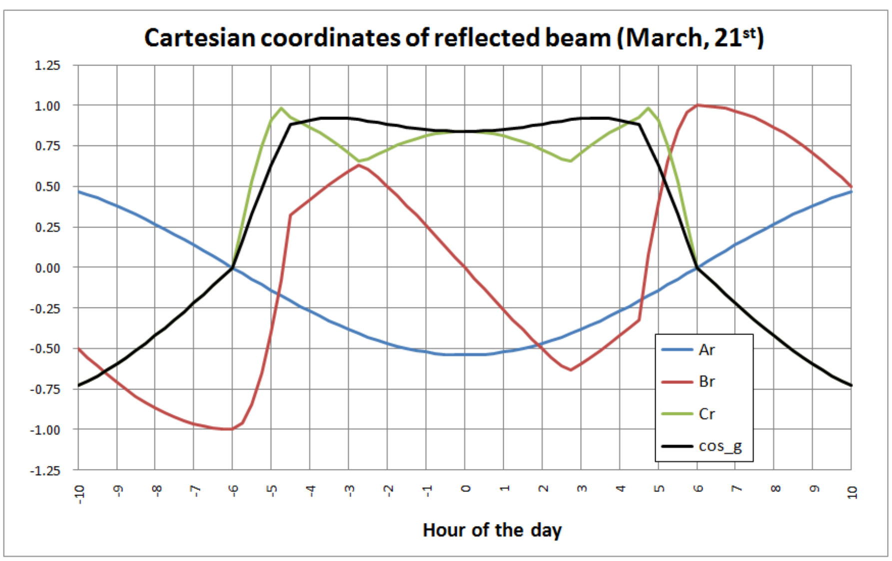


Fig 16.- Cartesian coordinates for reflected beam on a sample day. Incidence angle is very low, thus optimizing irradiance on PV modules with trackers.

3.5 Two axis tracker systems

PV systems with two axis trackers are considered independent reflecting planes. Each reflecting plane is geometrically defined by its perpendicular (normal) unit vector [n]. Notation for Cartesian coordinates of this normal vector is n = (Ap, Bp, Cp) in the reference coordinate system.

Because of the motion given by the two axis trackers holding the reflecting planes, the normal vector orientation changes with time. Actually, a perfect two-axis tracking system would continuously rotate the reflection plane so that the normal vector will always be pointing the sun. That way, the PV modules can collect as much direct irradiance as possible at any time, as shown in Fig. 17. As a consequence, the Cartesian coordinates of the normal vector are the same as for the solar vector. Following the notation descried in previous paragraphs, this can be written as:

$$Ap = A$$
$$Bp = B$$
$$Cp = C$$

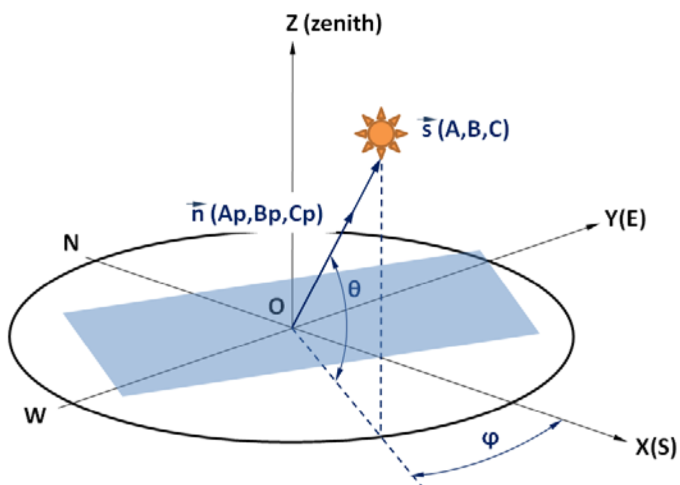


Fig 17.- Reflection surface normal vector coordinates

In practice, two-axis trackers have some tilt angle limitations due to constructive reasons, so a totally vertical position of the reflecting plane is not possible. The PV systems analyzed in this reports have a maximum tilt angle of 85°, as shown in Fig. 18.

Reflection of sun beams from a given surface can be calculated once the direction of the incident beam and plane orientation is known.

Instantaneous solar beam direction vector s = (A, B, C) and reflecting plane normal vector n = (Ap, Bp, Cp) intersects at the origin, and both defines a new plane in the space. From reflectivity laws, the reflected beam vector r = (Ar, Br, Cr) will be contained in this plane and symmetric to the incident beam with respect to the reflecting surface vector, as shown in Fig. 19:

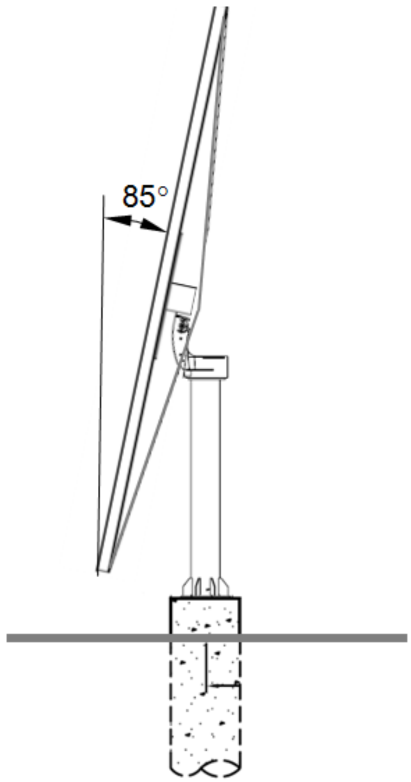
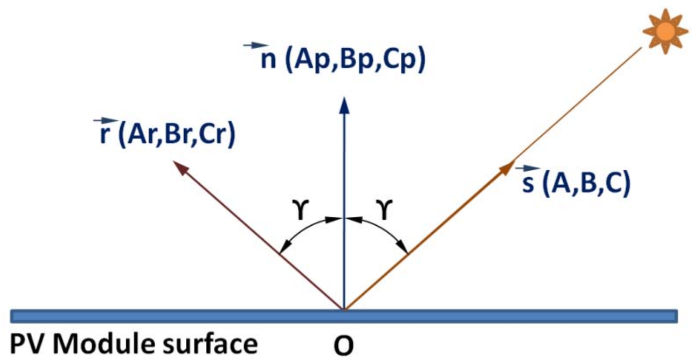


Fig 18.- PV system. Maximum tilt angle



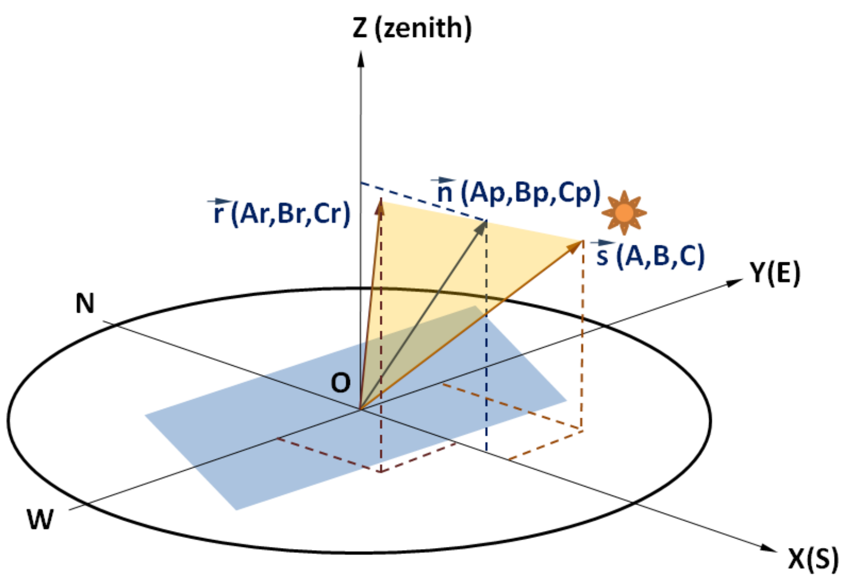


Fig 19.- Reflecting surfaces – Notation for reflected beam vector

As already stated, the incidence angle can be calculated as per the dot product of unit vectors [s] and [n]:

$$\cos\gamma = \vec{s}\ \vec{n} = A\,A_p + B\,B_p + C\,C_p$$

The symmetric-reflected vector [r] is calculated as

$$\vec{r} = 2\ \cos\gamma\,\vec{n} - \vec{s}$$

and its Cartesian coordinates given by:

$$A_r = 2\ \cos\gamma\,A_p - A$$
$$B_r = 2\ \cos\gamma\,B_p - B$$
$$C_r = 2\ \cos\gamma\,C_p - C$$

For example, for the equinox day chosen the results for (Ar, Br, Cr) are plotted below in function of the hour of the day. Incidence angle cosine also included. Note that the cosine of the incidence angle is equal to "1" for nearly all the day, as expected for double axis trackers.

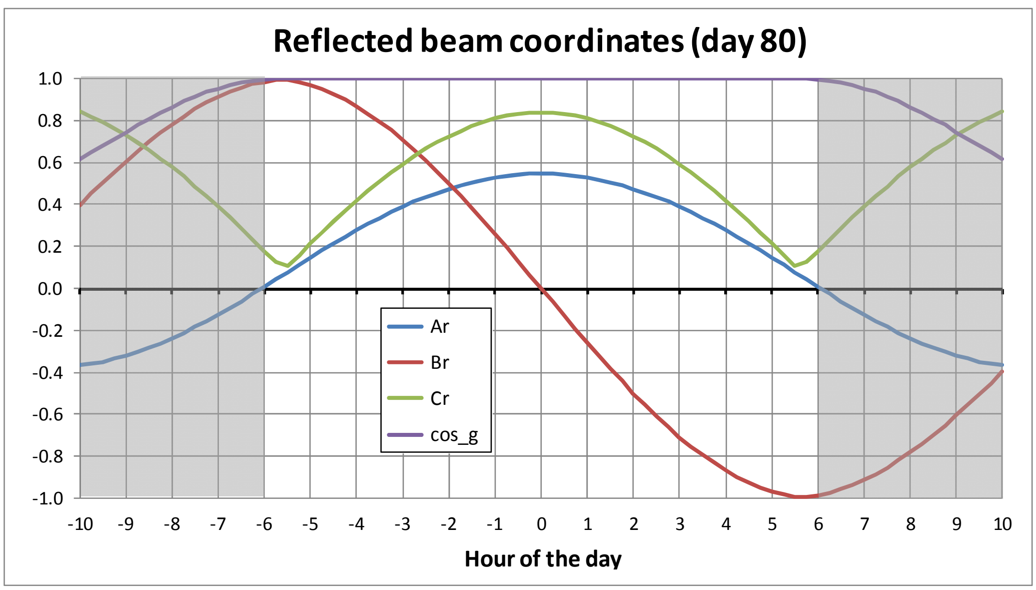


Fig 20.- Reflected beam vector coordinates and incidence angle with two axis trackers

4 Reflectivity results

To define the location of relevant KVP it is hereby assumed that the traffic roads around a given parcel do follow North-South or East-West directions. For the sake of simplicity, the shape of the sample parcel is considered a 2,600 ft x 2,600 ft square having straight roads at its four sides. The imaginary vertical planes containing the four roads are called respectively North, West, East and South planes, depending on their position relative to the parcel. These four vertical planes will be called "projection planes". The described geometry is shown in Fig. 21.

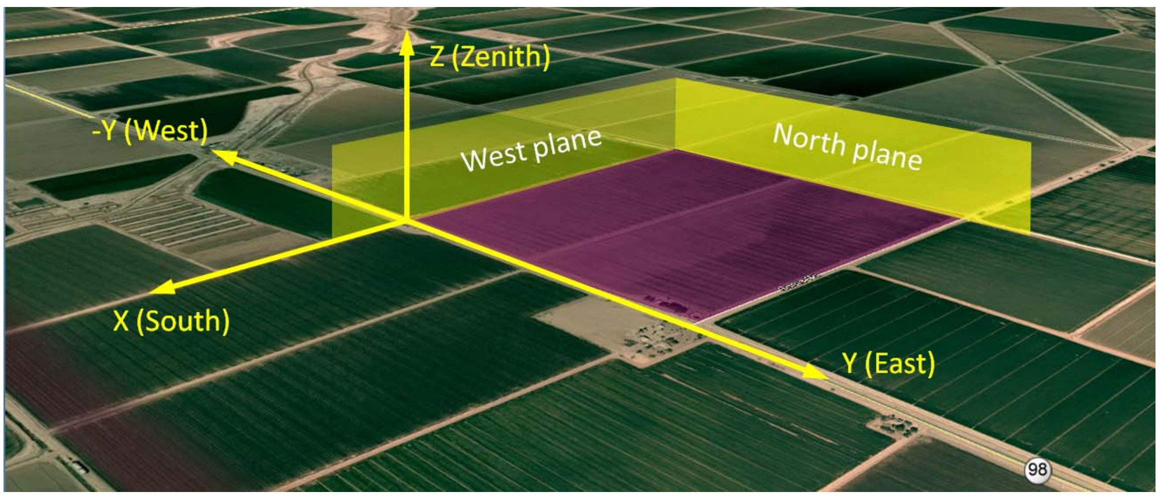
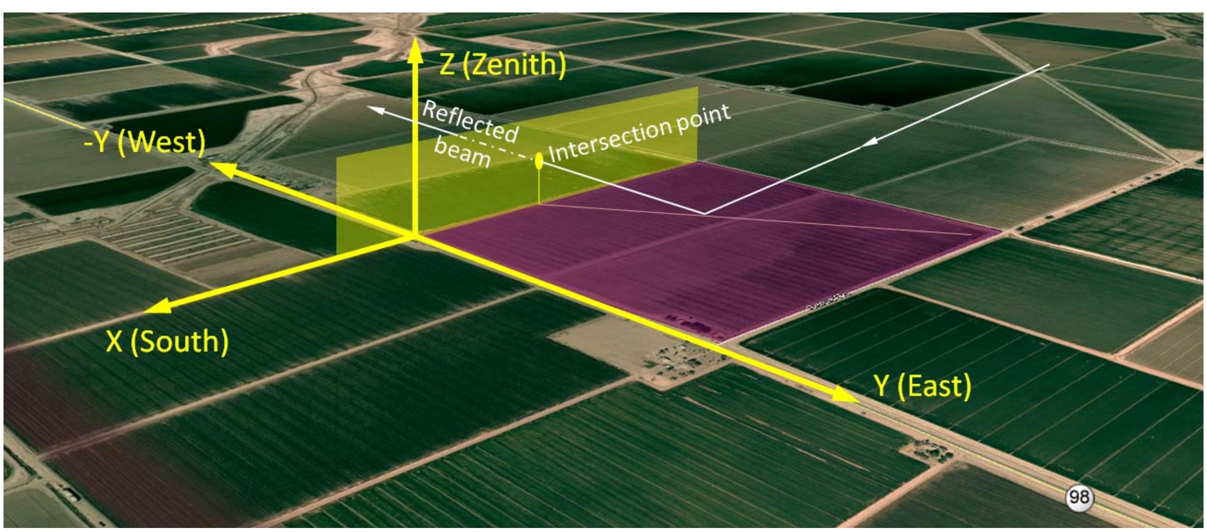


Fig 21.- Geometry of parcel, surrounding roads, and projection planes

Because of the reflective properties and orientation of the PV modules, a reflected solar beam may intersect one or other projection planes at a certain height from the ground. These will be called "intersection points".



Because the projection planes contains the respective roadways, there is a risk of glare for traffic on that roadway just if the height of the intersection point is lower than ten feet, being the ten feet threshold the height of the driver head in a large size truck. In other words, a glare event might occur if the intersection between the reflected beam and the intersection planes containing the roads occurs at a heigth of less than ten feet.

Fix tilt supporting structure

The position of the intersection points is different for each hour of the day, the day of the year, and the orientation of the reflecting surface. As an example, Fig. 22 below shows the reflection of the complete parcel at 8:25 am on day 80 (i.e., March 21) on the West projection plane. The East plane is symmetrical. The points in the graph are the intersection points on the projection plane at different hours of that day, being the (0,0) origin located at the North-West corner or the parcel.

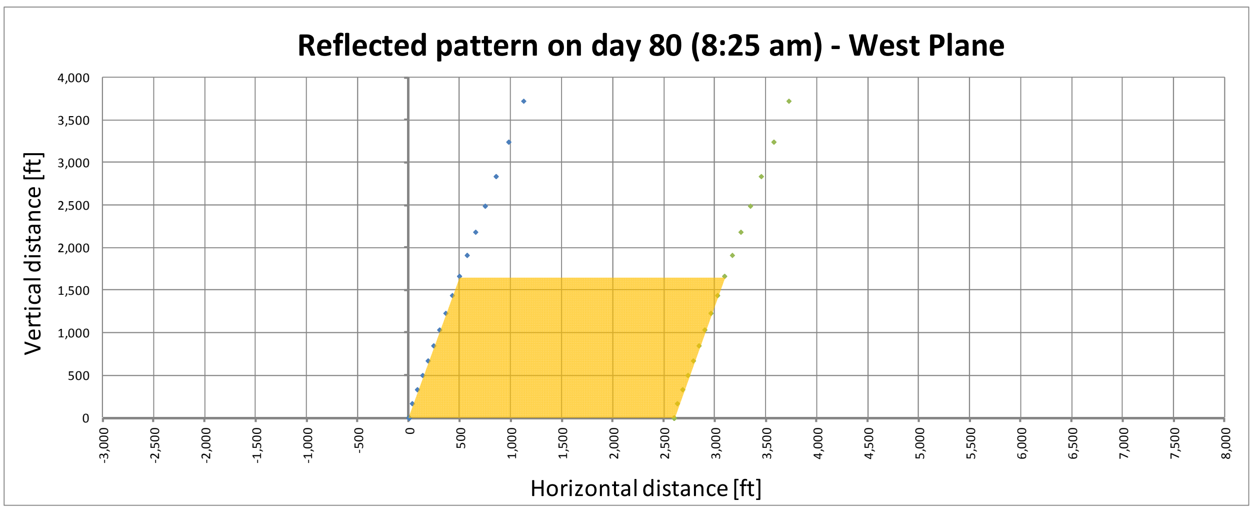
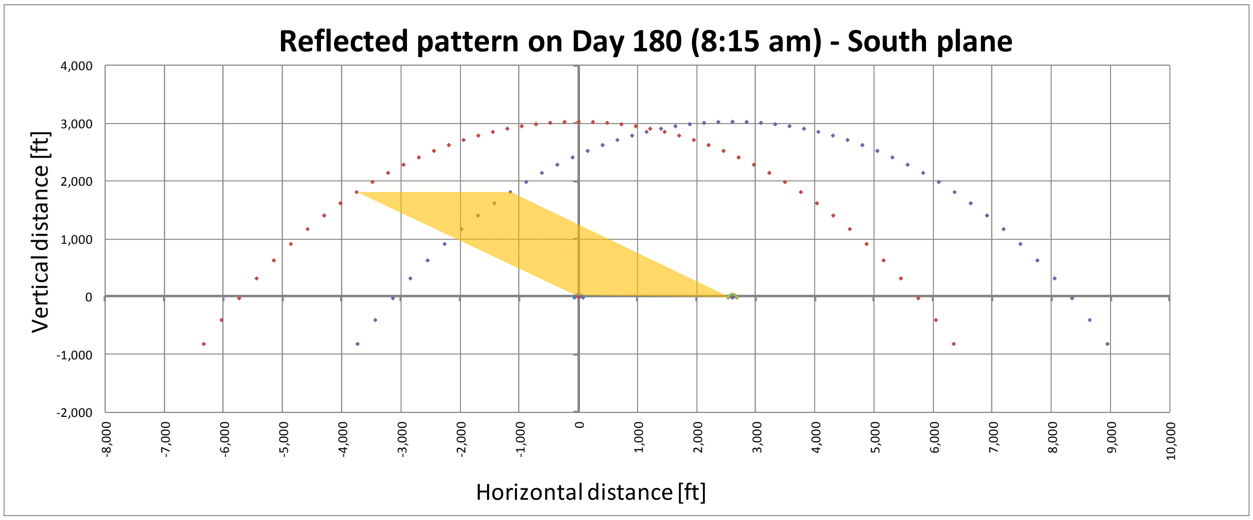


Fig 22.- West projection plane on March 21.

Because reflection can reach the ground level, there is a risk for glint in both the West and East roadways, however this occurs when the sun is at very low elevation angles, thus the driver will actually suffer a more intense glare from direct visual exposure to the sun disk, rather than because of the eventual reflection from PV modules.

For the South projection plane, there is risk of glint during summer season and no risk in winter season. Because of the reflection pattern, the sun disk is not necessarily aligned with the driver and the modules, so a slatted fence is recommended in the South side of the parcel (Figs. 23). No reflection will ever occur in the North side of the parcel.



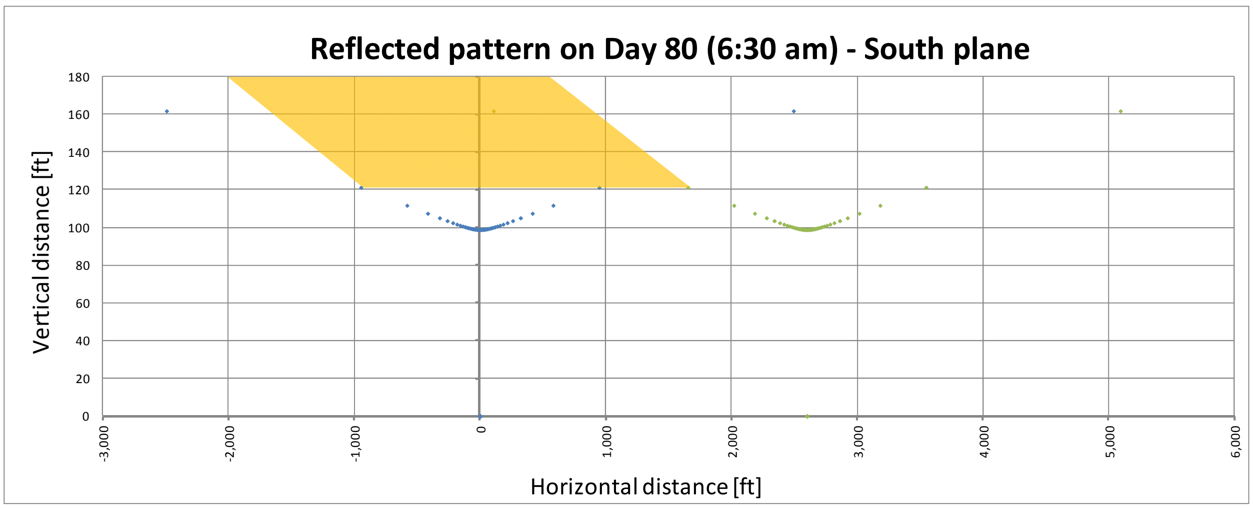
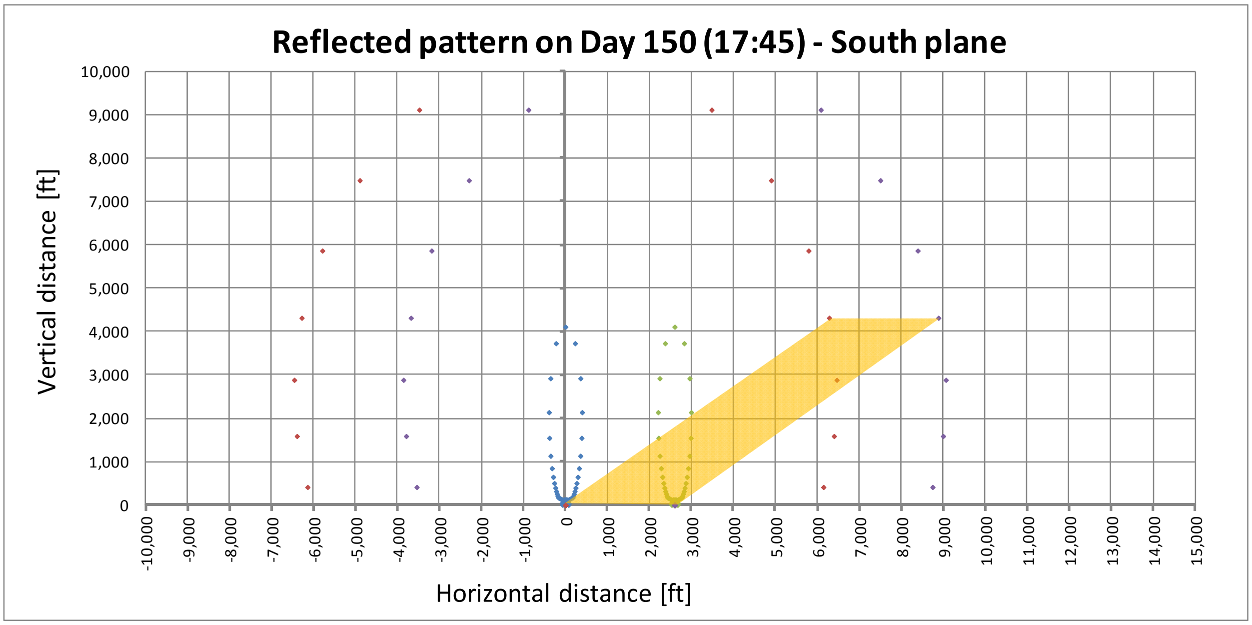


Fig 23.- South projection plane in summer and winter days.

One axis tracker supporting structure

Because trackers move the PV modules towards the sun's position, the risk of reflection greatly decreases with respect to fix the tilt case. The following graphs show the reflection pattern of the sample PV plant on each of the projection planes for selected days (Fig. 24, 25 and 26).



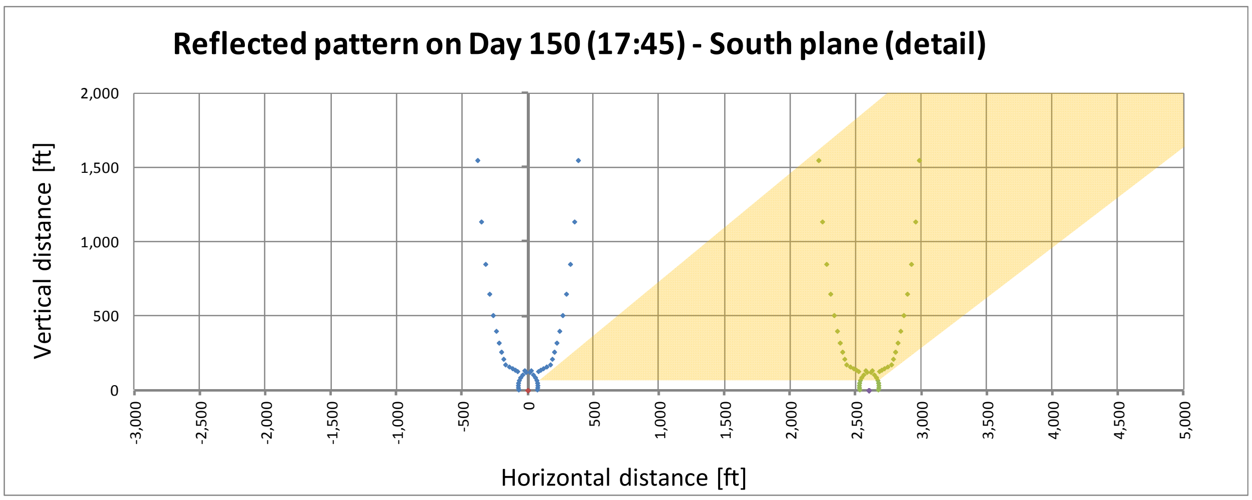
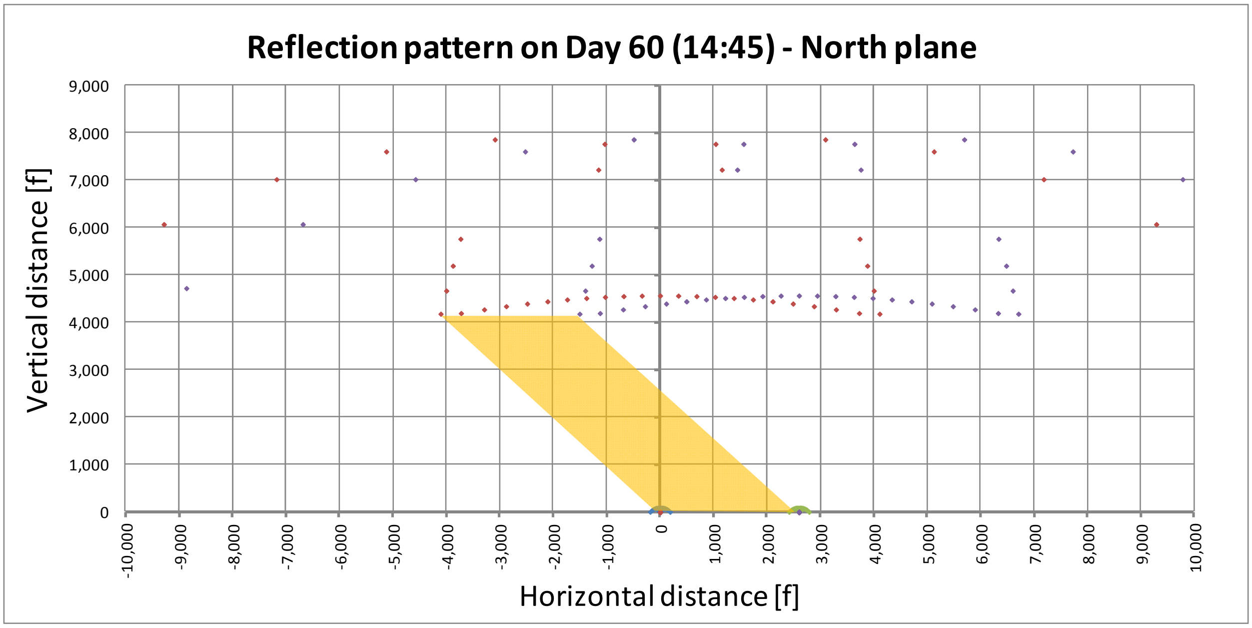


Fig 24.- South projection plane

As shown in Fig. 24 the reflection may reach the ground level at South side only at sunset and sunrise hours. This is because of the backtracking algorithm that tends to keep the PV modules in horizontal position in that specific time of the day. As a consequence the sun disk will be always aligned with the driver eyes during any glare event.

A similar situation is found in the North plane. The detail shows that mid-day reflections will be over 40 ft height on the roadway plane (Fig. 25) in winter. That minimum height of the reflection point is due to the fact that there is a 30 ft buffer distance between the PV modules and the roadway itself. The farer from the modules the higher the reflection point height will be.



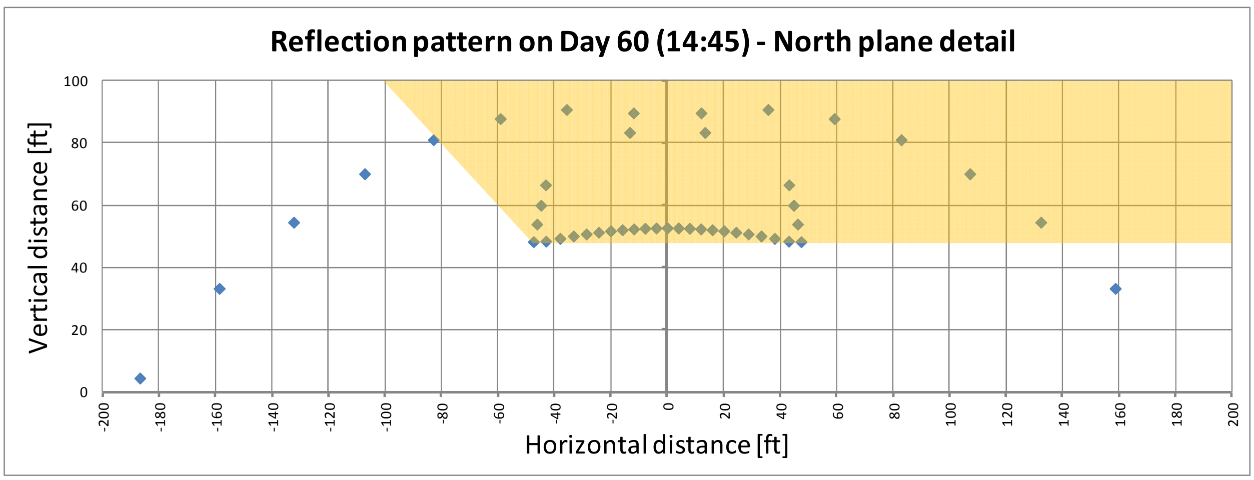


Fig 25.- North projection plane

The traffic on East and West roadways planes might also have some glare effect, but in all cases these would happen during early morning and late afternoon because of backtracking position, thus the observers will directly face sun disk simultaneously. This is shown in Fig. 26 for day 80.

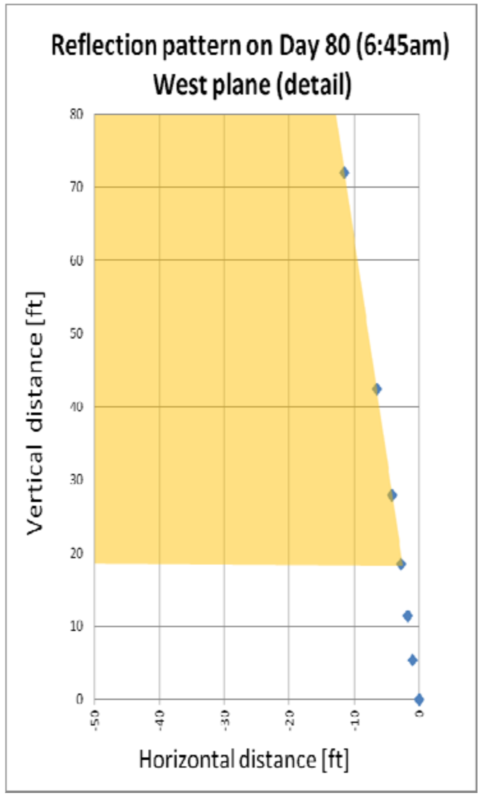
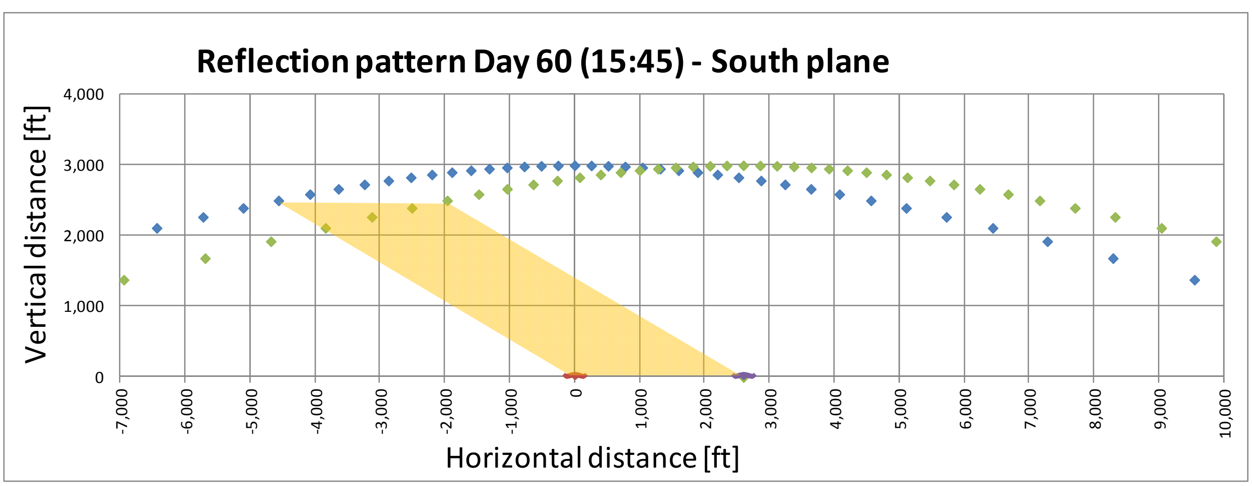
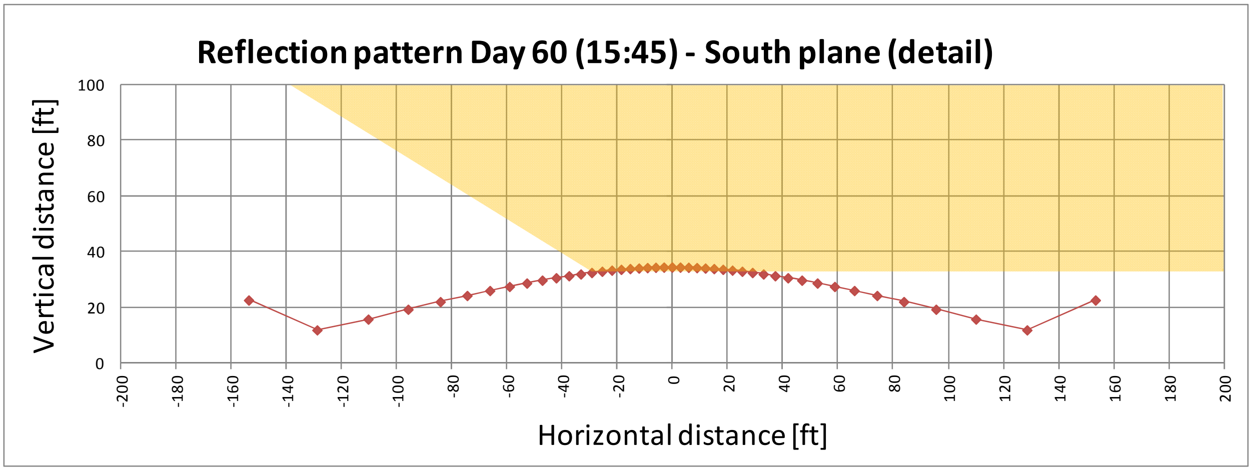


Fig 26.- West projection plane (East symmetrical)

Two axis tracker supporting structure

The results for the two axis tracker option are shown in the following graphs. The reflection point will be over 40 ft above the ground surface at the South boundary. As examples for the South plane case, the following graphs show two typical days in winter and summer:





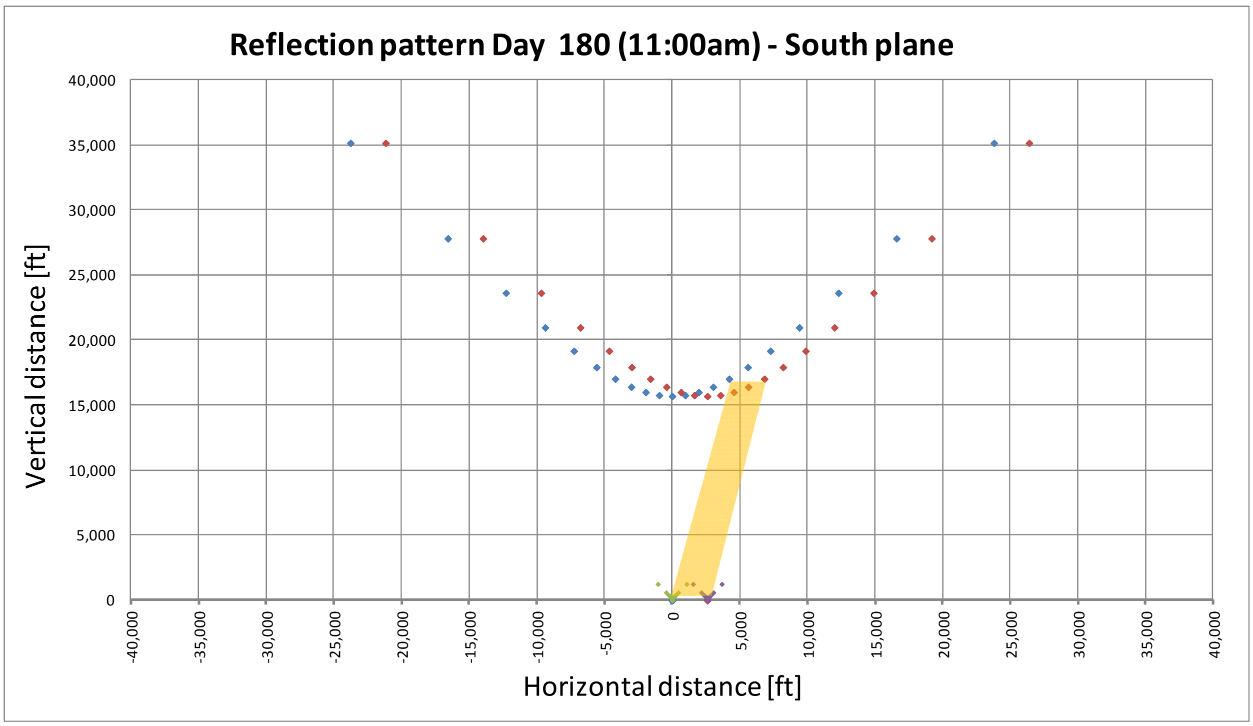
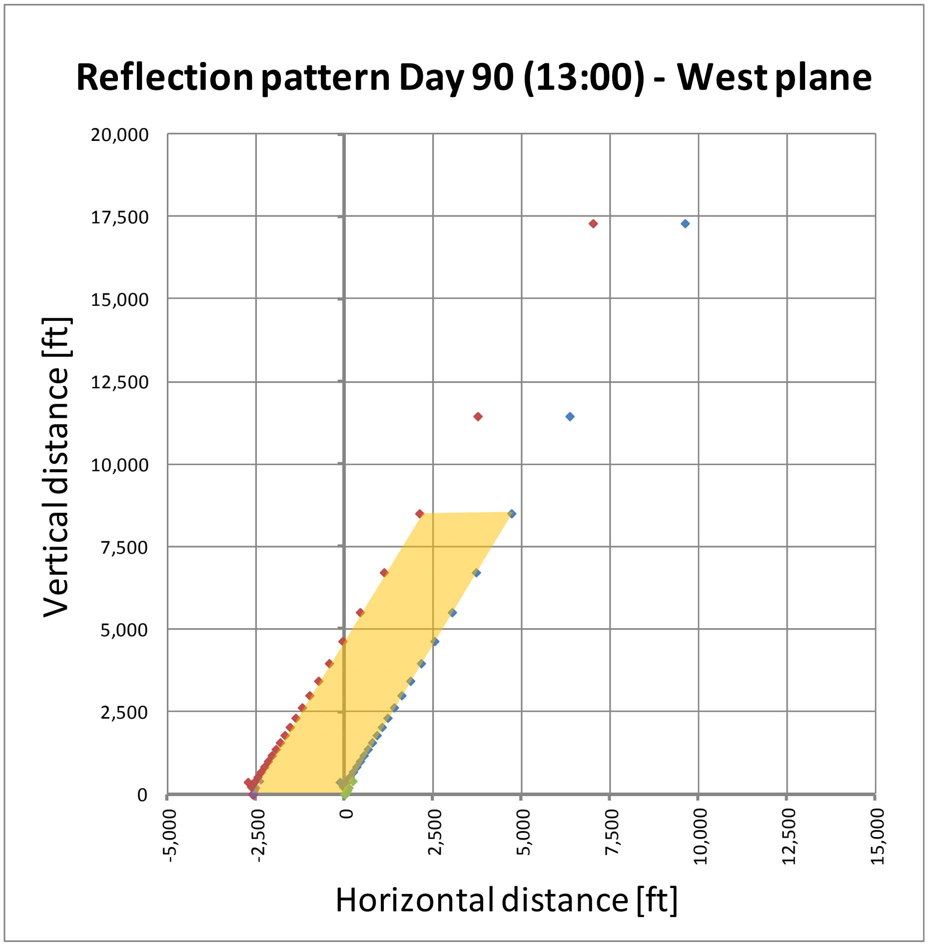


Fig 27.- South plane projection in selected days

Because of the nature of two-axis trackers, there is no possibility to have any glare event in the North plane (as it was the case for fix tilt structures).

For East and West projection planes the results in Fig. 28 reveals that the reflection point could be low enough to cause glare during sunrise and sunset. In this case, the sun disk will be in opposite direction from the PV modules. It is recommended to install slats in the East and West sides of the project fence to avoid glare effects.



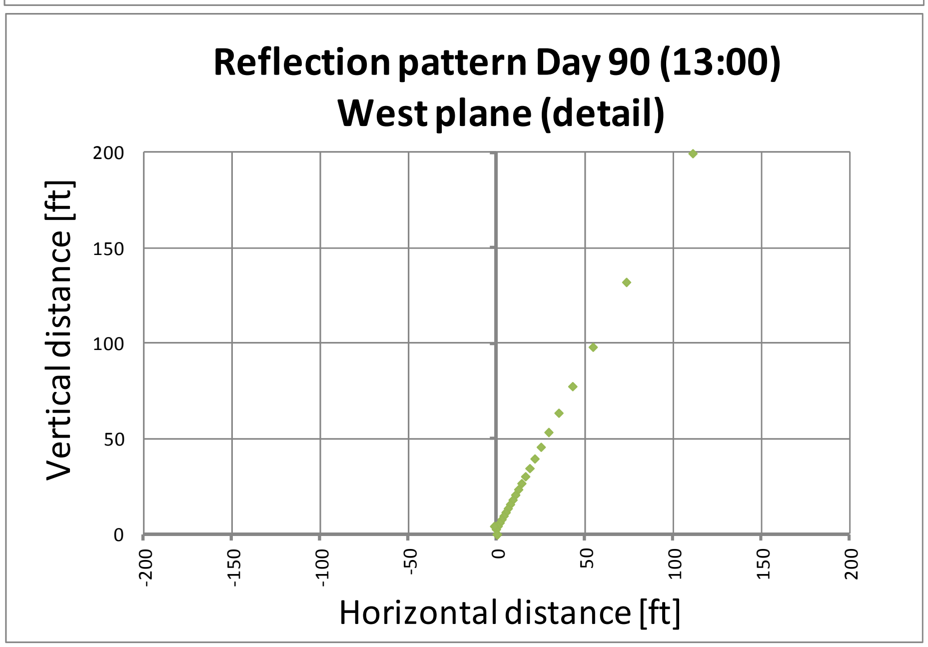


Fig 28.- South plane projection on selected sample day

5 Conclusion

PV installations are based on flat photovoltaic modules with low reflectivity characteristics. Just 10% of the incident radiation is reflected, but this might still produce some glint to KVPs. For this Project, it is considered that land traffic in roadways around the proposed parcels might be exposed to certain degree of glint.

To determine the glint risk, a geometric analysis is done. The analysis is conducted for a complete year in intervals of 15 minutes (that is 35,040 points). All mathematical expressions for sun position, orientation of PV modules and reflected sun beams are implemented in a computer routine to evaluate the risk of glint. This is done for three different module supporting structures: fix tilt, one axis trackers, and two axis trackers.

The following table summarizes the calculated results regarding glare exposure risk for roadways located North, South, East or West of each of the parcels:

Supporting structure	Roadway position	Additional risk of glare
Fix Tilt	North	NO
	South	YES
	East	NO
	West	NO
Single axis trackers	North	NO
	South	NO
	East	NO
	West	NO
Double axis trackers	North	NO
	South	NO
	East	YES
	West	YES

As a countermeasure for glare risk, it is recommended to install fence slats in corresponding parcel's boundaries based on the table above. As an example, the proposed distribution for fence slats for the Fix Tilt case (South boundaries) is shown in Fig. 29.

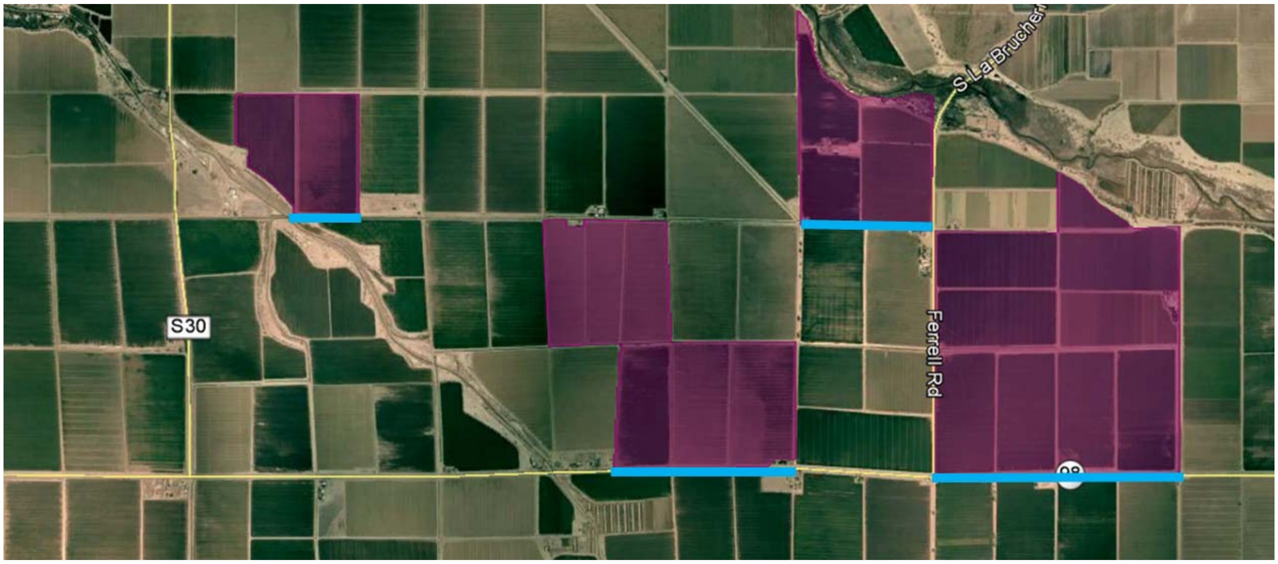


Fig 29.- Proposed location of fence slats to protect traffic in Hwy98 and Kubler Rd (Fix tilt scenario)