APPENDIX G

Glare Analysis for Air Traffic

MOUNT SIGNAL Solar Farm (82LV 8ME, LCC)

REFLECTIVITY ANALYSIS

REVISION INDEX

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1 Introduction

This document analyzes the risk of sun reflectivity due to a series of photovoltaic (PV) power plants being developed by 82LV 8ME, LLC. Project location is nearby the Calexico airport in Imperial County, CA. Reflectivity events due to the presence of PV modules might affect airplane visibility while approaching the corresponding airport runway if reflected sun light beam intersects the approaching flight path.

Fig. 1 shows the location of the future PV plant relative to Calexico airport.

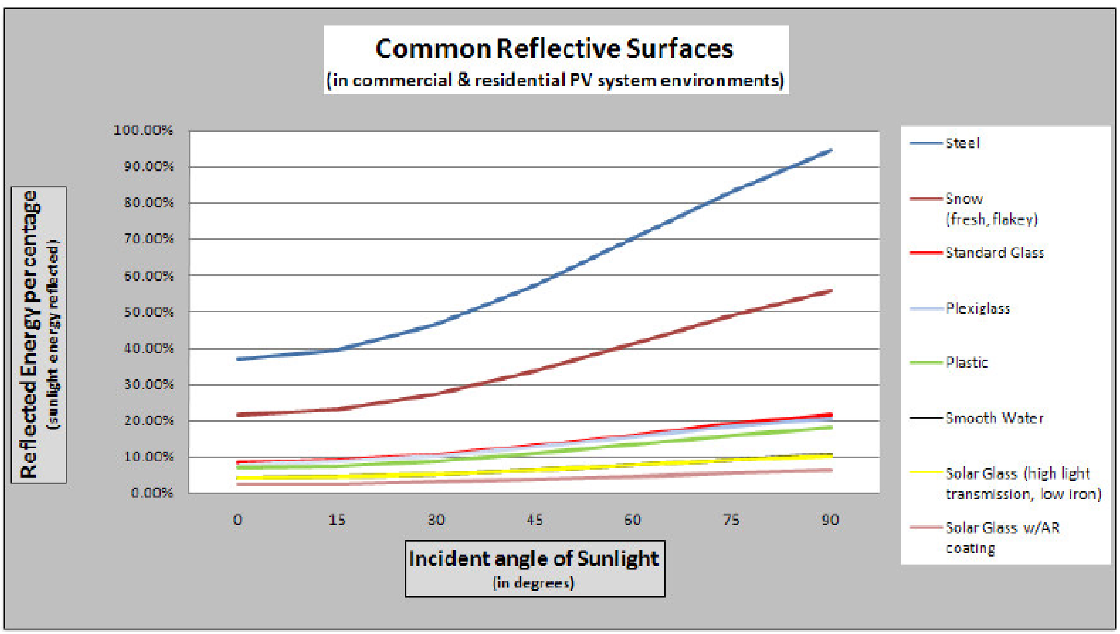
Fig 1.- Location of PV Project and Calexico airport

To evaluate the risk of direct sun light reflection events a mathematical (geometric) model has been developed. The model predicts when in the year there is a possibility for approaching or taking-off airplanes to suffer direct reflection.

2 Definitions

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

Photovoltaic Module – Photovoltaic panels, also known as PV modules. By nature, PV panels are designed to absorb as much of the solar spectrum as possible in order to convert sunlight to electricity. Reflectivity levels of solar panels are decisively lower than standard glass or galvanized steel, and should not pose a reflectance hazard to viewers. The next graph relates the reflectivity properties of solar modules in function of the incidence angle, and compares with other common reflecting surfaces in an airport environment:



Reflected light from PV modules' surface is just between 10% - 20% of the incident radiation, as low as 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 be tangent to the reflecting surface) and, in this case, the intensity of incident light is much lower than -say- noon time.

Glint – Also known as a specular reflection, produced by direct reflection of the sun beam in the surface of the PV solar panel. This is the potential source of the visual 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 have negligible effects. As Glare is the reflection of diffuse irradiance is not directional. Other glare sources in the nature (often called Albedo reflectance) are much more intense that glare from PV modules, for instance even agricultural environment has higher Glare effect than PV modules.

Key View Point (KVP) – KVPs are viewpoints used in the glint and glare study. In this analysis, KVP can be any point in the most probable airplane approaching path to the airport runway.

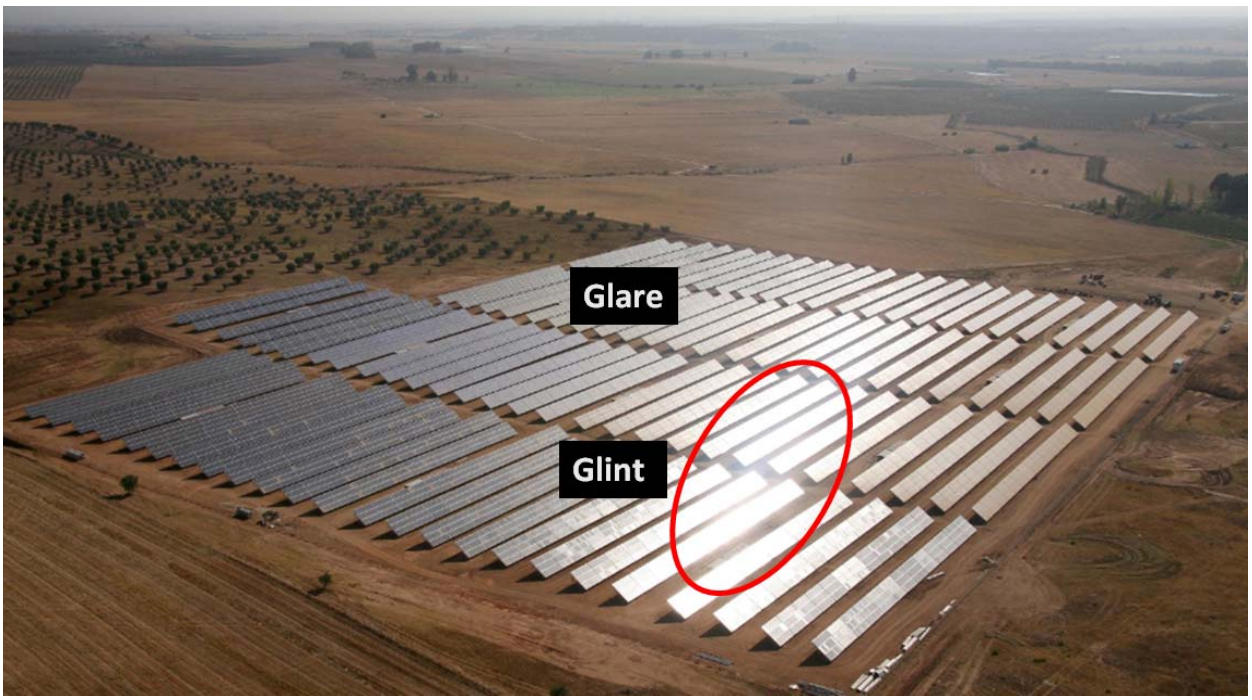


Fig 2 .- Glint and Glare identification from a PV installation

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 KVP location; is necessary to define a global coordinate system to which the previous position and orientation will be referred to.

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

Origin of the coordinate system is chosen at the future PV plant location, as shown in Fig. 3 below:

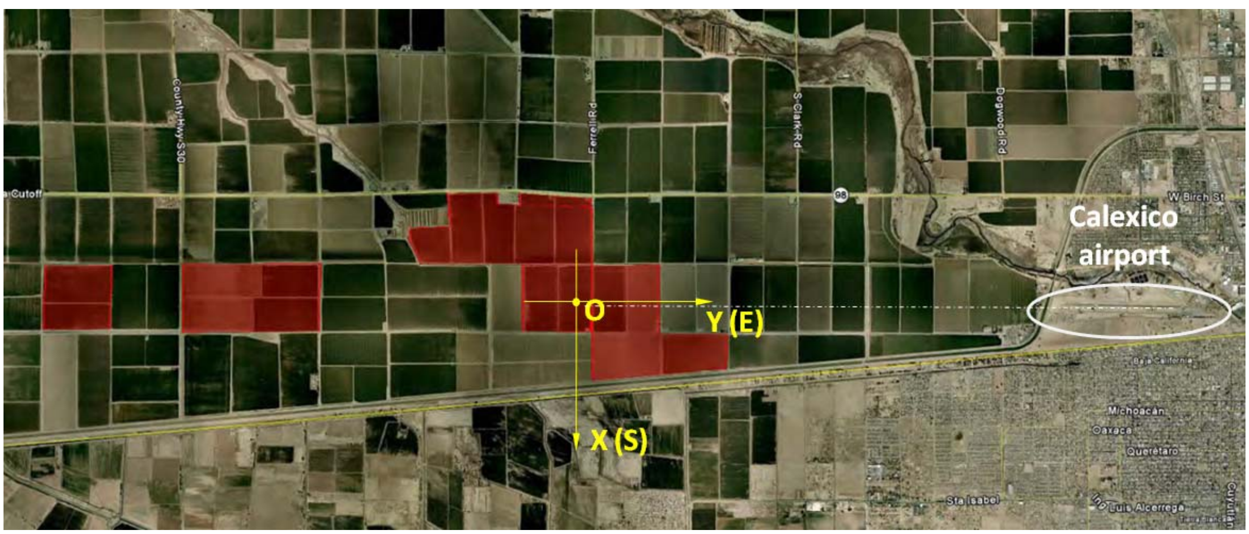


Fig 3 .- Reference coordinate system

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 above definitions, and criteria for positive values:

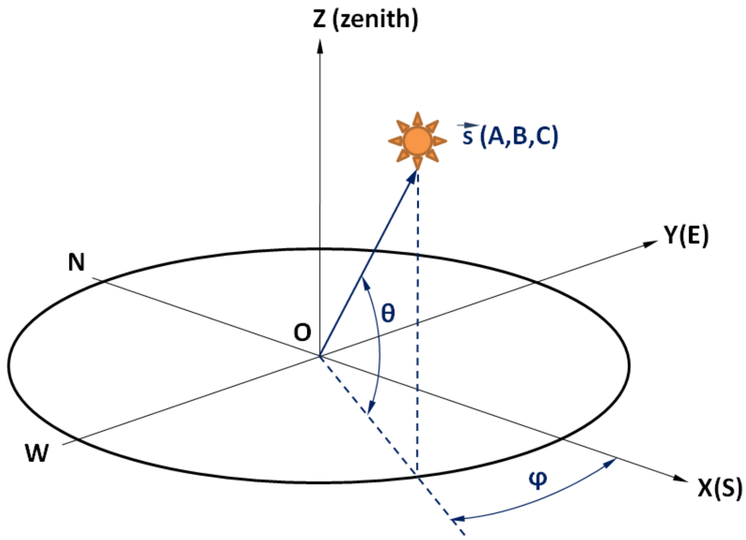


Fig 4.- Sun position coordinates

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 the next graph:

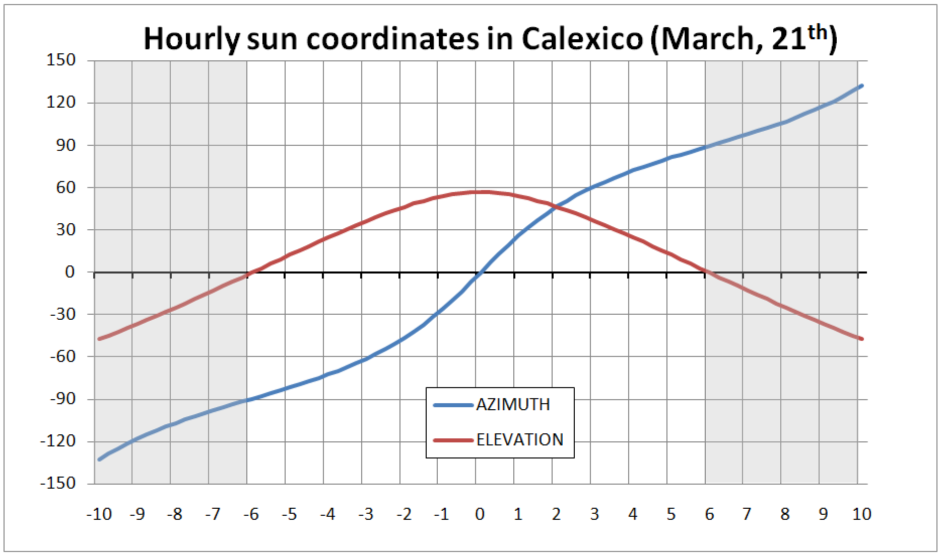


Fig 5.- Sun position coordinates in function of hour of the day

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. 6:

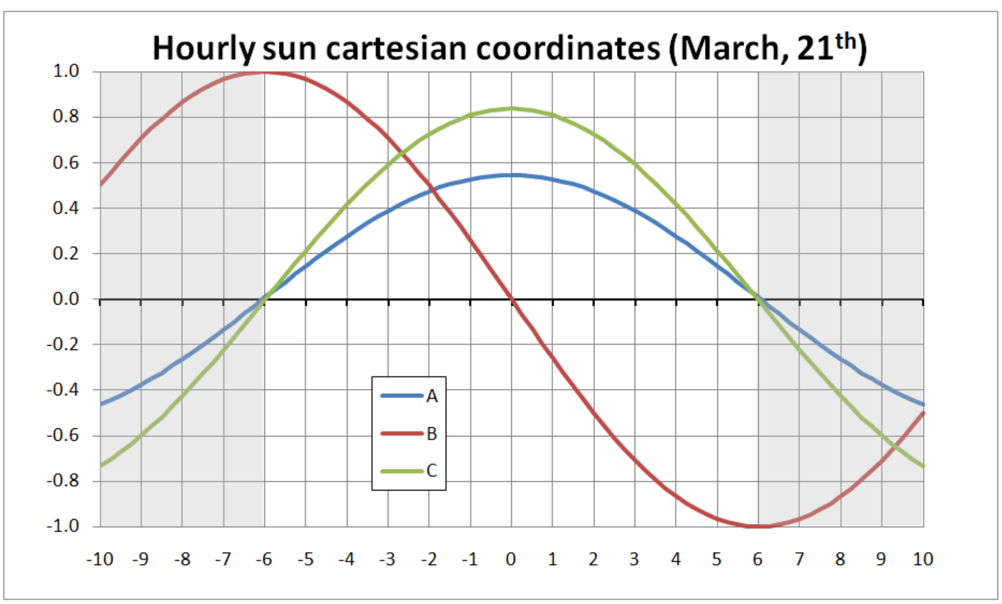


Fig 6.- Sun position Cartesian coordinates in function of hour of the day

3.3 Reflection equations for fixed tilt system

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. 7.

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

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

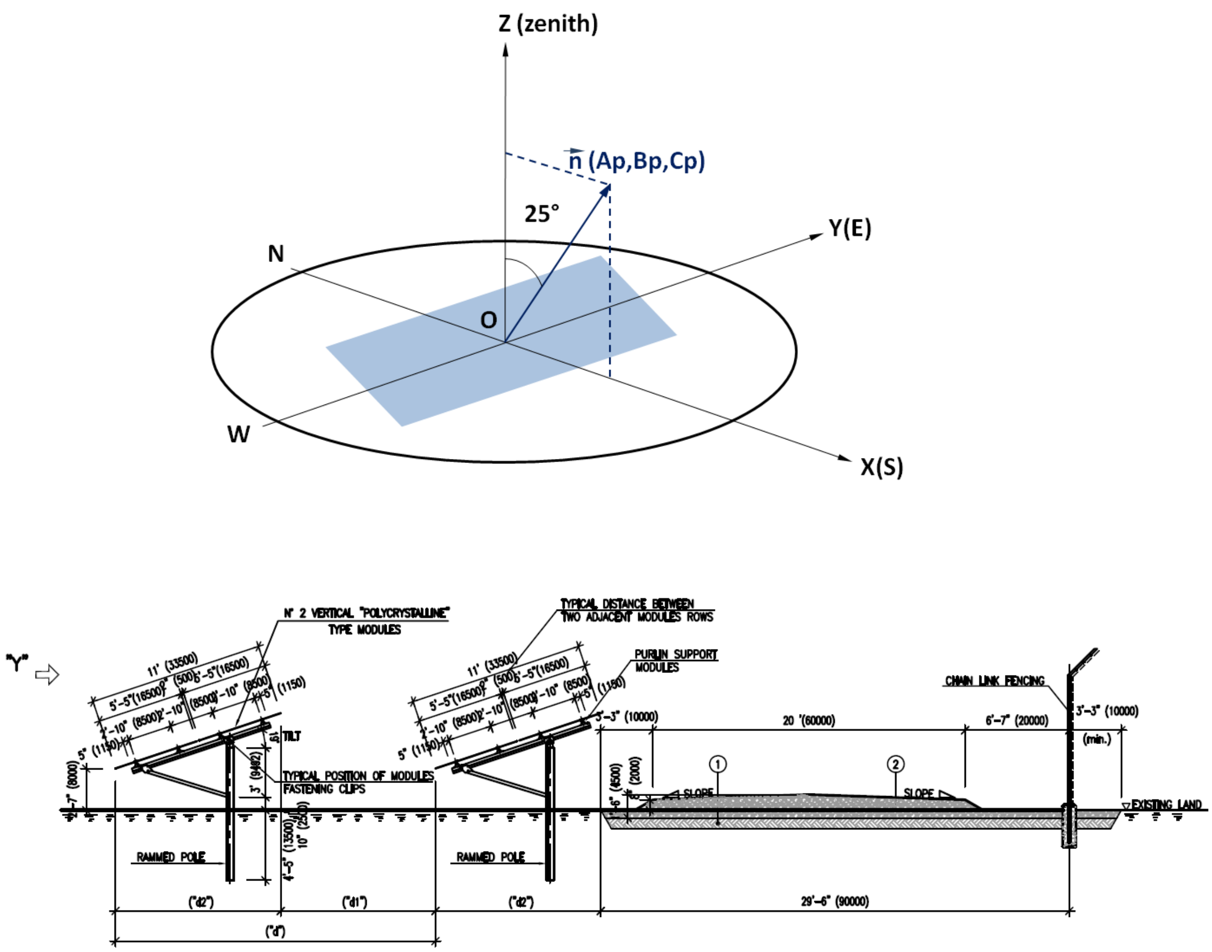


Fig 7.- Reflecting surfaces – Coordinates and typical PV design

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:

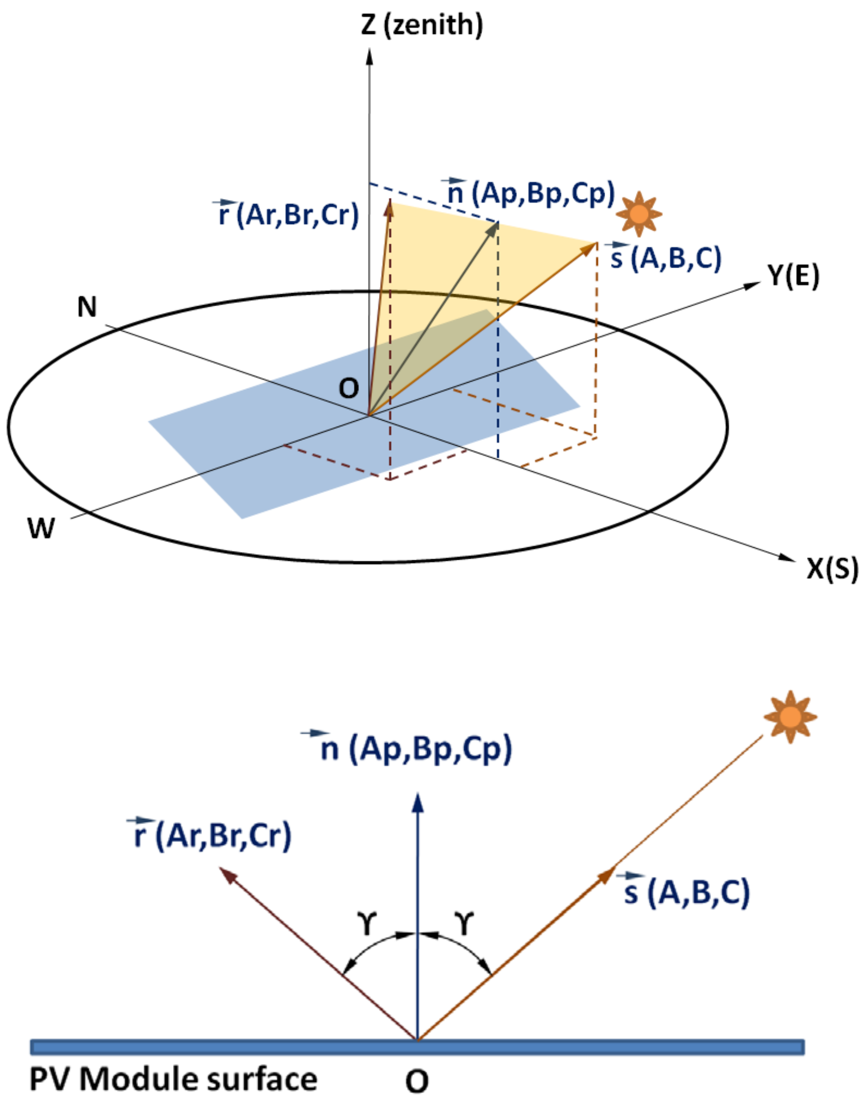


Fig 8.- Reflecting surfaces – Notation for reflected beam vector

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.

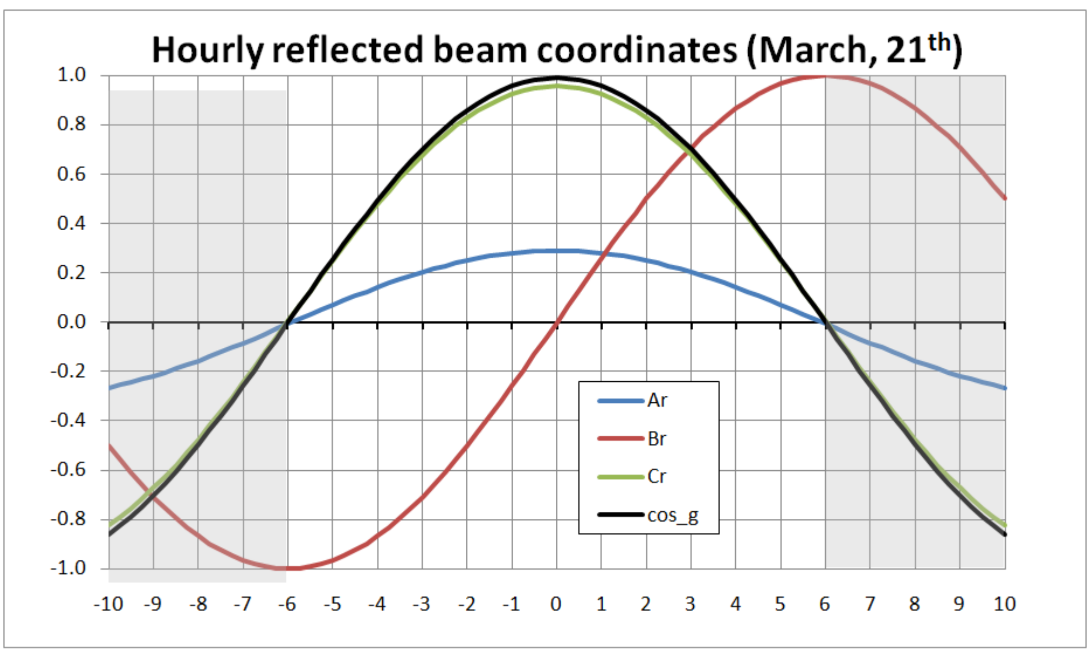


Fig 9.- Reflected vector coordinates and incidence angle

3.4 Flight plane and reflectivity at Calexico runway (fixed systems)

To define the location of relevant KVP it is hereby assumed that the approaching airplane follows a straight line contained in a vertical plane (the "flight plane") that also contains the runway axis (Fig. 10).

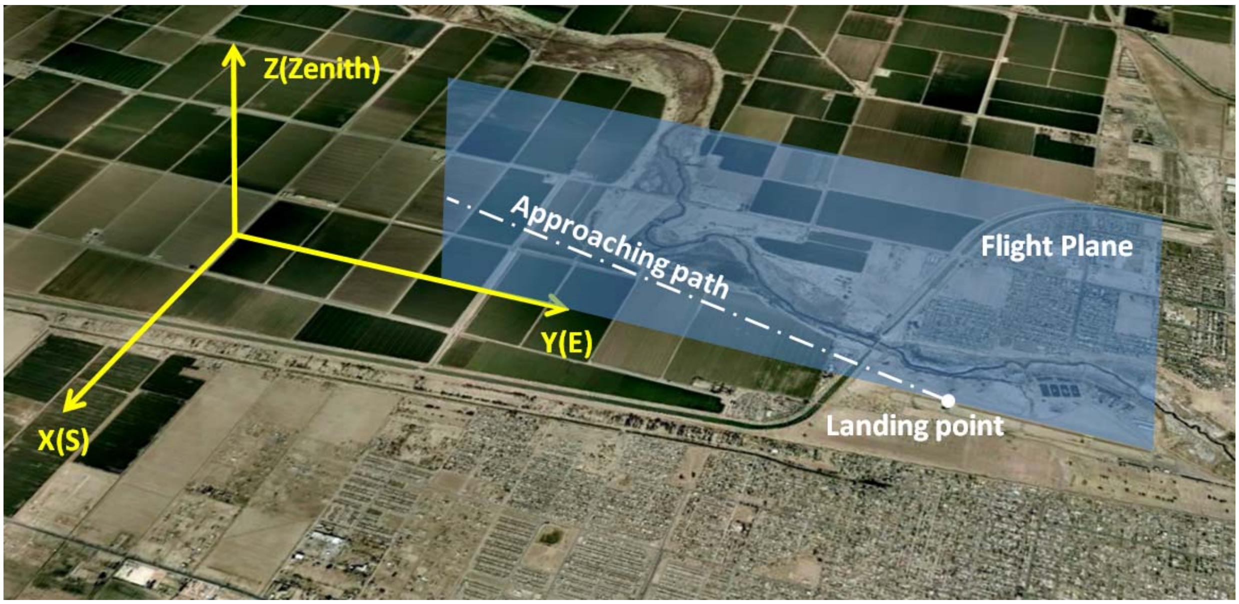


Fig 10.- Geometry of approaching path

The vertical flight plane, containing the approaching path, is defined by the following equation in the reference Cartesian axis system:

$$\Pi \equiv 0.9997\ x - 0.0239\ y = 0$$

The flight plane contains the PV plant, as shown in Fig.3. Several days along the year and at certain hours, a reflected beam vector will be contained in the flight plane, but relevant glint might occur only if the elevation angle of the reflected beam is coincident with the flight approaching angle, in either East or West directions.

Runway azimut is 88.63°. Cartesian coordinates for any reflected beam r = (Ar, Br, Cr), if contained in the flight plane, shall satisfy the following condition (beam azimuth):

$$\frac{B_r}{A_r} = \tan\ 88.63° = 41.814$$

The angle between the horizontal plane and the reflected vector (reflection elevation angle) is given by

$$\tan\theta_r = \frac{C_r}{\sqrt{A_r^2 + B_r^2}}$$

Fig. 14 shows the hourly evolution of the above functions for a sample day (March, 2nd)

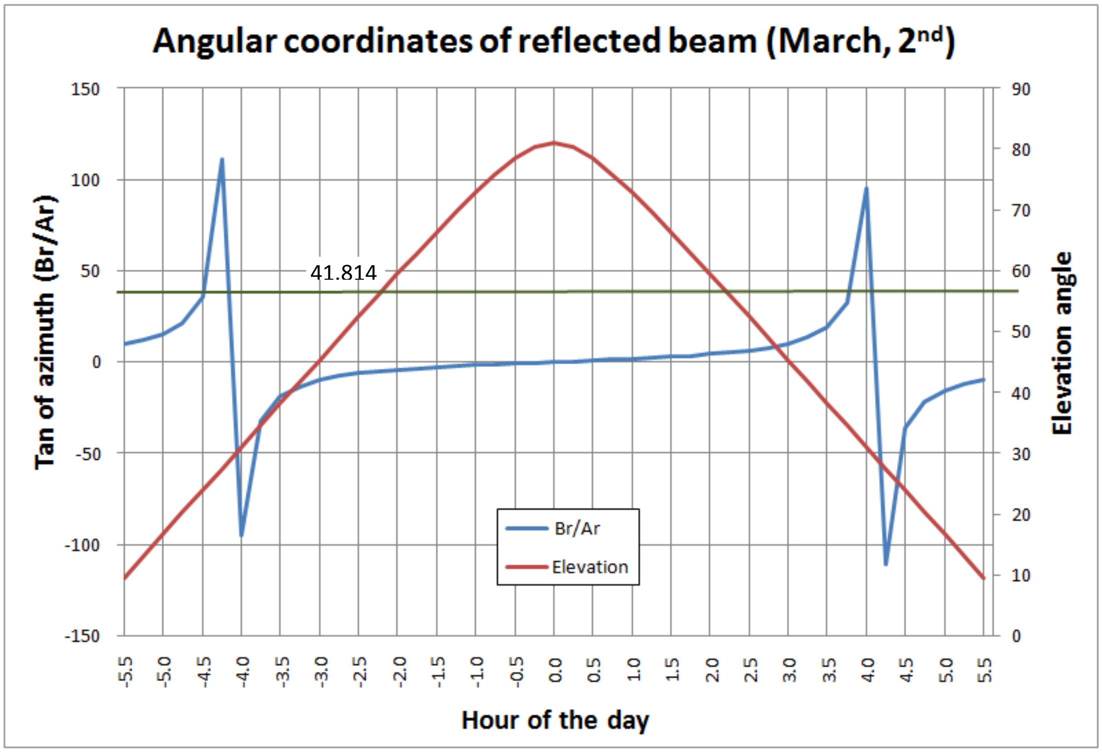
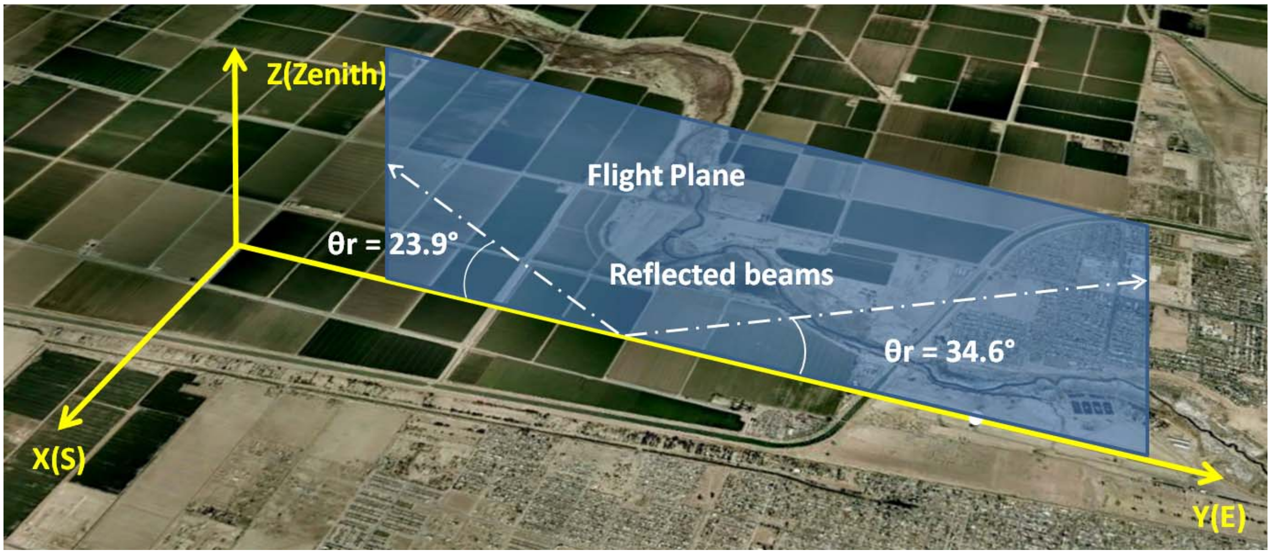


Fig 14.- Angular coordinates of reflected beam (March, 2nd)

It can be seen that the reflected beam will be contained in the flight plane at 07:30h (after sunrise) and at 15:45h (before sunset). The reflected beam will be pointing upwards with an angle of 23.9° and 34.6° respectively.



Obviously, the reflection held at 07:30 would affect airplanes landing Calexico from West, while the reflection held at 15:45h would afect airplanes landing or launching from East. In both cases, a long-term glint exposure would only occur if the airplanes were landing at the same particular angles (i.e., 23.9° and 34.6° respectively). It should be noted that normal landing angles are within the range of 3° and 6°, so in this particular day no risk of prolonged glint is possible.

The same procedure is repeated for all days in a year. Results in Fig.15 shows the elevation angle of the reflected beam in function of the day, whenever the in-plane condition occurs. Bandwith between estimated minimum and maximum airplane landing angles (3° and 6°) is superimposed :

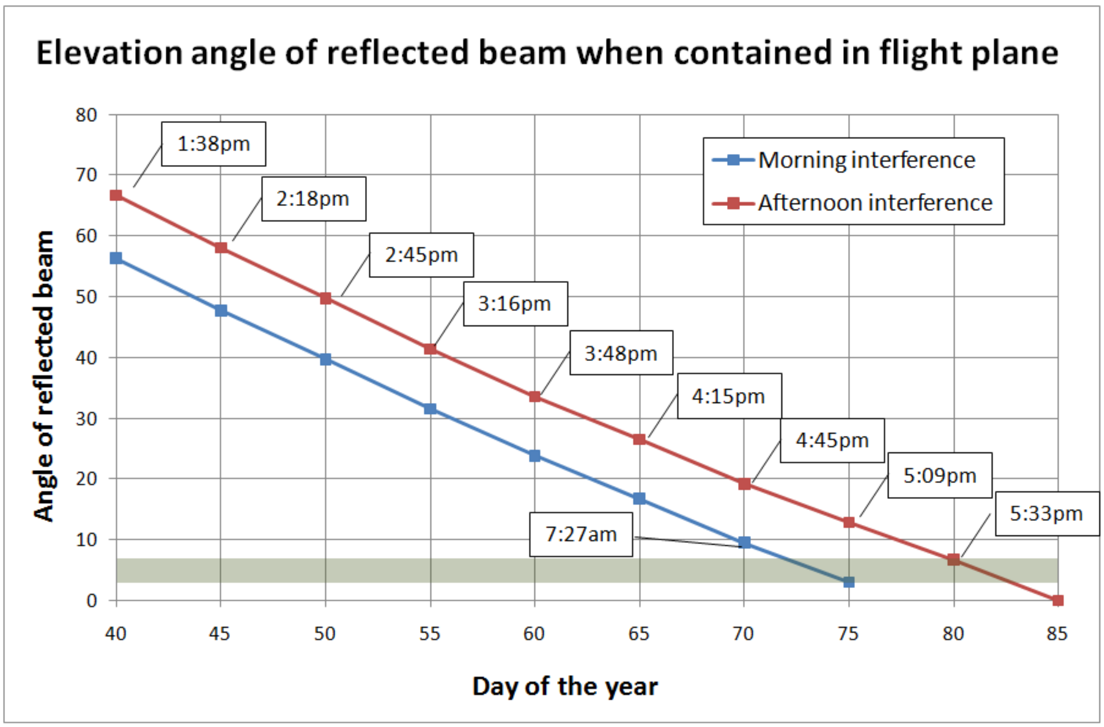


Fig 15.- Reflected beam elevation angle and landing angles – Runway 29

There are a few days in the year where there is an eventual risk of glint from the PV modules to landing airplanes. These particular days are 72 to 75 (2nd week of March - morning time) and 80 to 83 (3rd week of March - evening time). Because of yearly simmetry, the same occurs in mid-October.

Fig. 16 shows sun coordinates for a typical day in these periods (day 73). Interference with landing path occurs at around 07:37 hours, sun azimuth is -84° and elevation only 3°. Therefore airplanes reaching Calexico airport runway from the West end will have the sun disc just in front of them. It is considered that glint effect is neglegible when compared to direct sun light exposure, as in this case.

Similarly, planes landing or launching from the East at day (say) 82, will be facing the sun disc at sunset, and again the risk of glint is negligible when compared to the light intensity of direct sun.

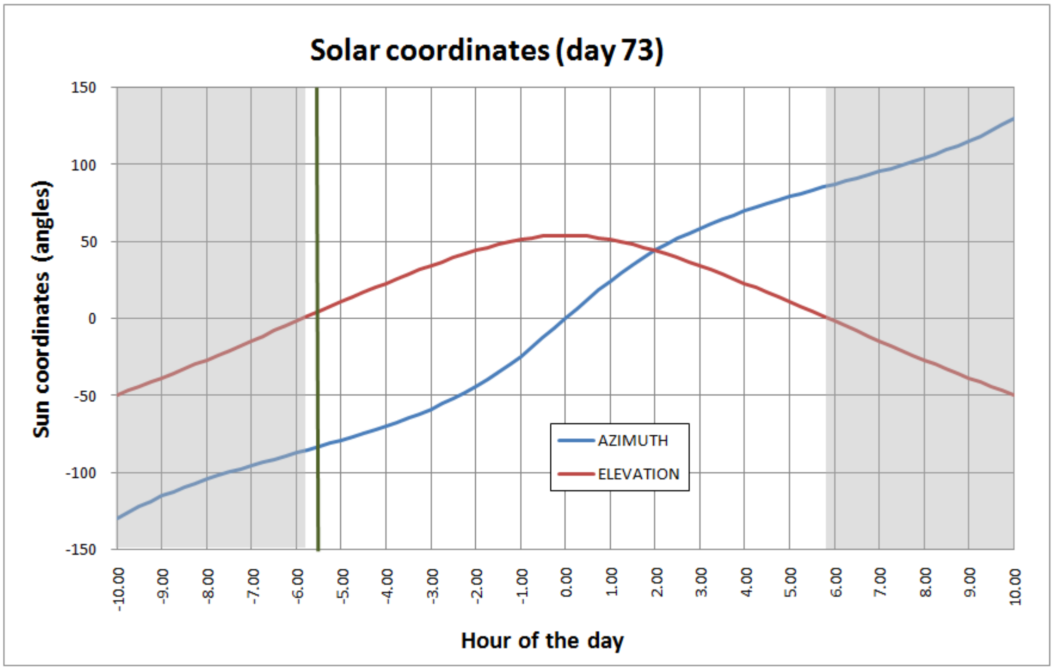
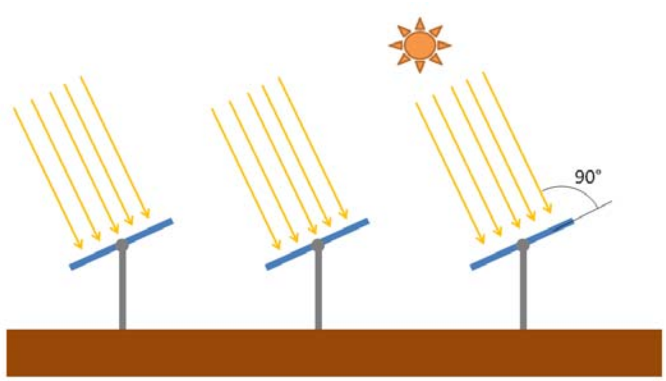


Fig 16.- Sun postion for selected typical interference day – Green vertical line shows time of interference with airplane landing path.

3.5 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.



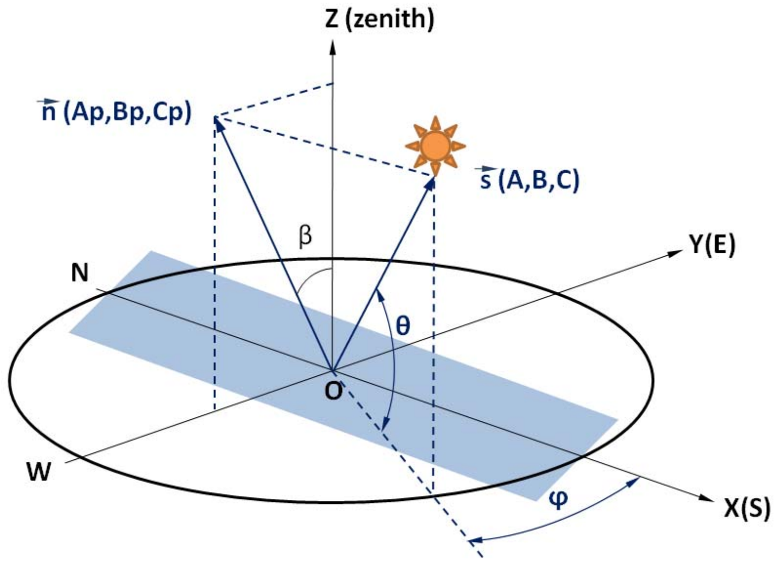


Fig 17.- Normal vector to PV modules in an horizontal axis tracker

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

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

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.

3.5.1 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.

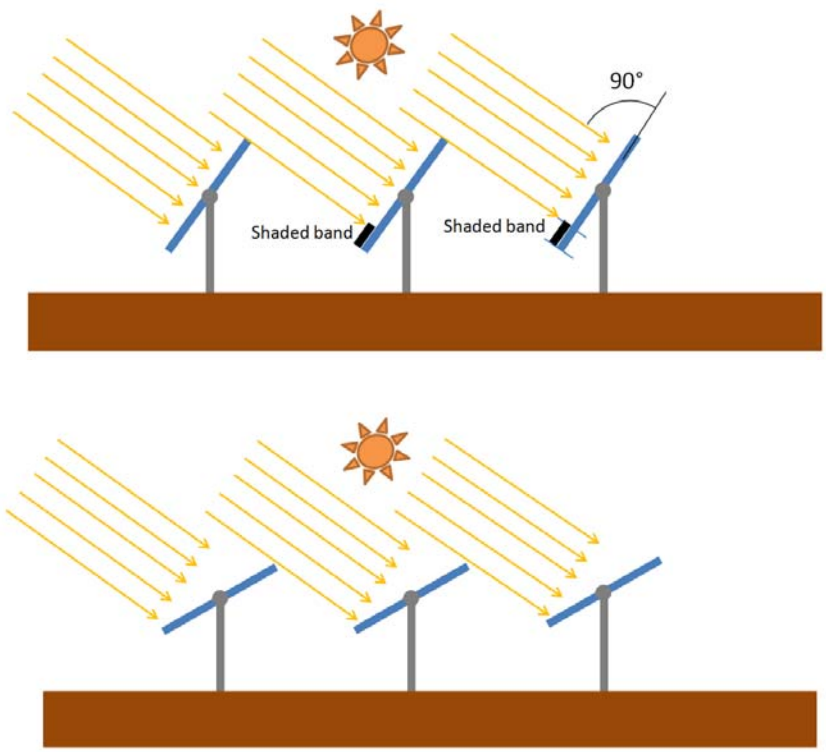


Fig 18.- Above: Mutual shading without backtracking.
Below: Backtrackin corrected incidence angle to avoid mutual shading

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

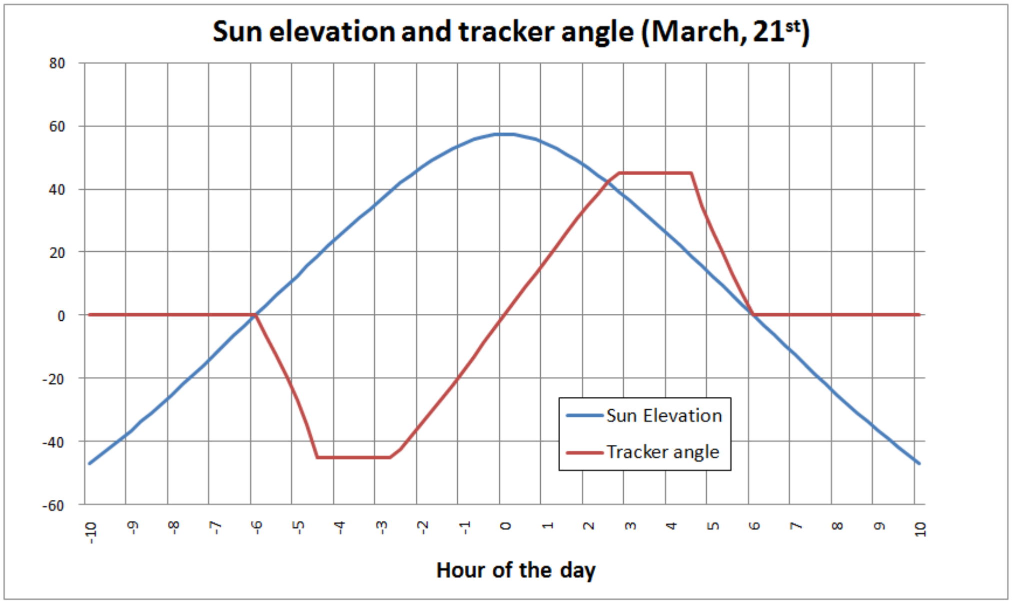


Fig 19.- Tracker angle on a sample day

Cartesian coordinates of the reflected beam, and incidence angle are shown in Fig. 20,

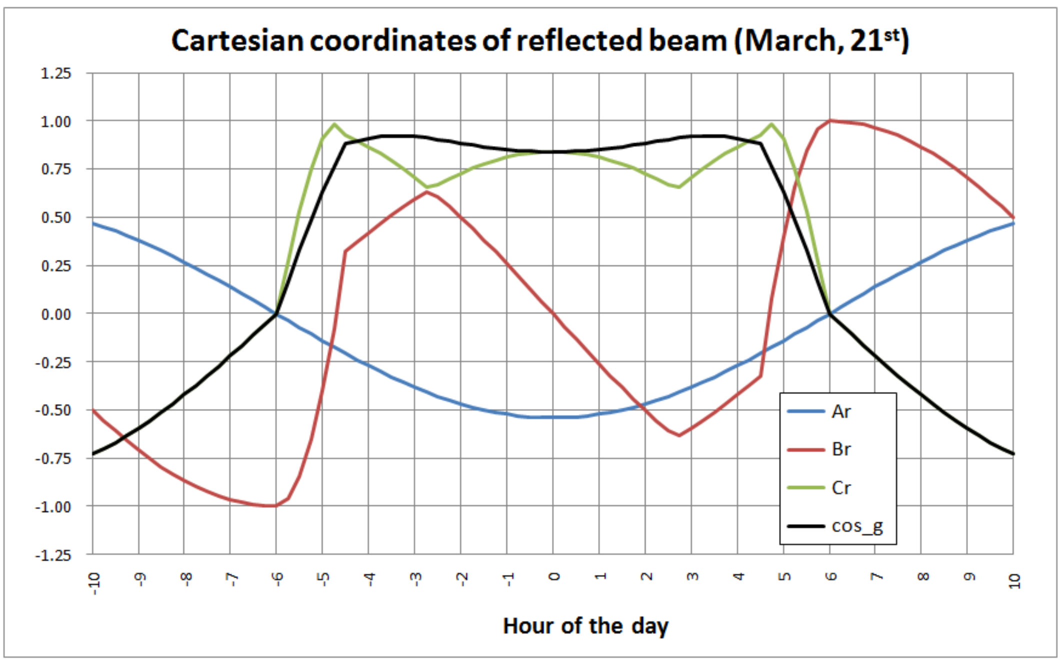


Fig 20.- Cartesian coordinates for reflected beam on a sample day. Incidence angle is very low, thus optimizing irradiance on PV modules with trackers.

3.6 Reflectivity analysis with horizontal axis trackers at Calexico

The procedure described in 3.4 is repeated now for the moving reflecting surfaces. The flight plane contains the PV plant, as shown in Fig.3. Several days along the year and at certain hours, a reflected beam vector will be contained in the flight plane, but relevant glint might occur only if the elevation angle of the reflected beam is coincident with the flight approaching angle, in either East or West directions.

As an example, Fig. 21 shows the azimuth and elevation angle of the reflected beam. The green line defines the flight-plane azimuth condition for Calexico, thus the reflected beam will be contained in this particular plane at 8:45am and 3:00pm, but in both cases the beam elevation angle is well over 40°, so there is no risk for glint.

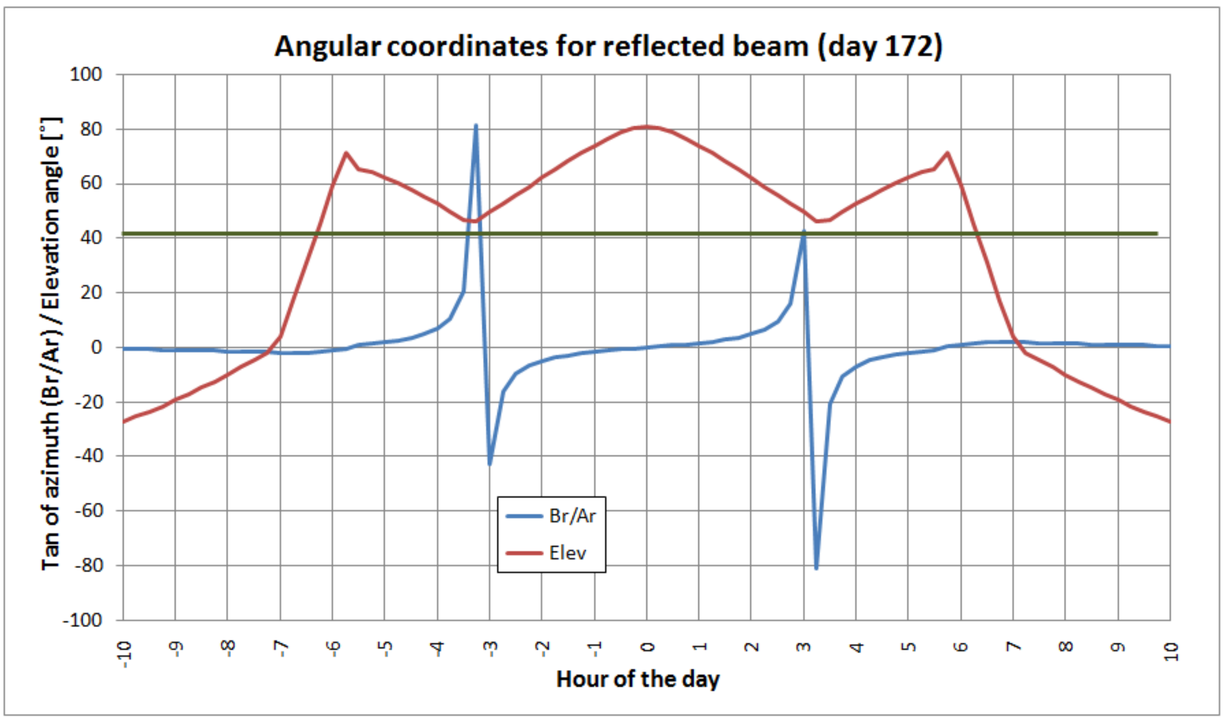


Fig 21.- Angular coordinates for reflected beam (day 172)

The same calculation is repeated for a complete year and results shown in Fig. 22.

It can be seen that whenever the reflected beam is contained in the flight-plane, its elevation angle is very far from the usual approaching or launching angles to the airport, so there is no risk of glint with trackers.

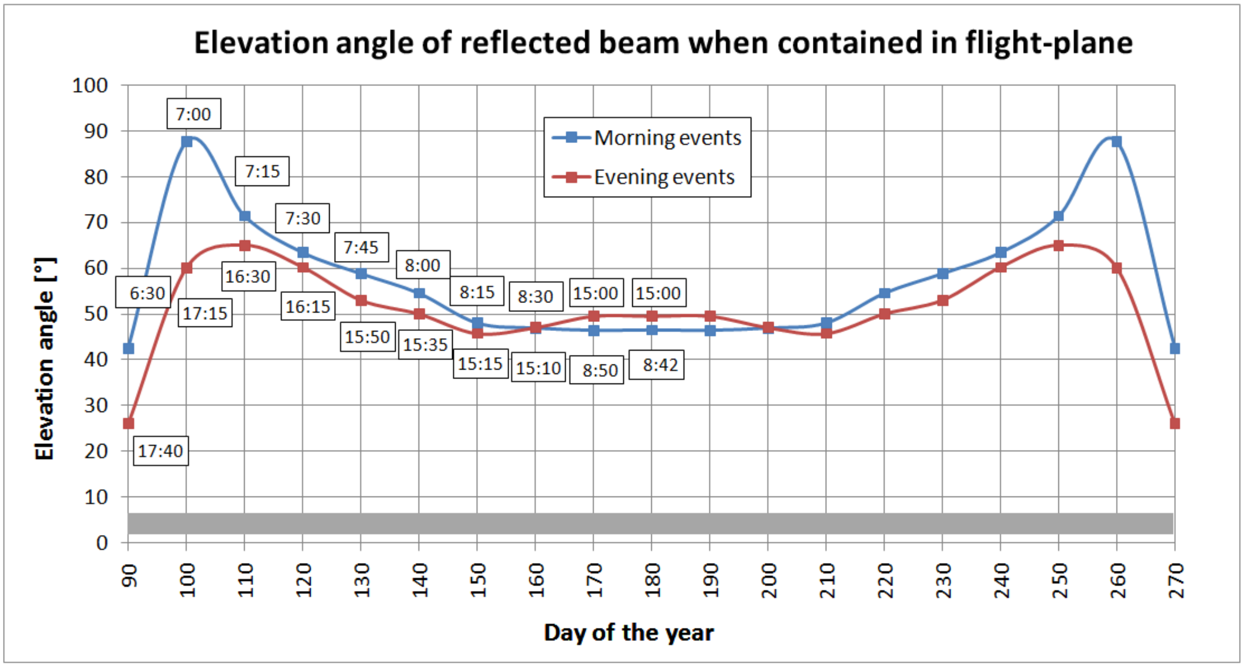


Fig 21.- One year results for elevation angles of reflected beam when contained in the flight plane. For the six month period from October to March the reflected beam is never contained in the flight-plane.

4 Conclusion

PV installations are based on photovoltaic modules with low reflectivity characteristics. Just 10% of the incident radiation is reflected, but this might produce some glint to KVPs. For this Project, it is considered that airplanes landing at or taking-off from Calexico airport might be exposed to glint.

To determine the glint risk, a geometric analysis is done for both scenarios: Fixed tilt PV modules and Horizontal Axis trackers. The analysis is conducted for a complete year in intervals of 15 minutes (that is 35040 points). All mathematical expressions hereby described are implemented in a computer routine.

In the case of fixed tilt PV fields it has been demonstrated that, in the few cases when there is some risk of glint by PV modules, the airplane will also be directly facing the sun disk, so it can be concluded that glint from PV modules will not have any relevant effect on airplanes' visibility, nor deteriorate the actual approaching or launching flight conditions.

If the PV plant is built with horizontal axis tracking technology, the eventual reflected beam would have a high elevation angle (that is, pointing upwards), so no interference with approaching or launching airplanes from Calexico airport will ever occur.

The same conclusions can be extended to other tracking technologies (single inclined axis or double axis trackers). With these devices, the tracking efficiency is higher than with horizontal axis trackers, therefore the incident angle is even lower, and the reflected beam will be pointing the sun disk more closely. Risk for glint when landing of launching might theoretically occur only at low sun elevation angles (i.e., sunrise or sunset); however, during these particular hours the backtracking technology modifies the tracking algorithm to avoid mutual shading thus re-orientating the reflected beams upwards, far from the flight path.

It is concluded that this Project will not have any relevant glint effect for airplanes landing at or taking-off from Calexico airport. This is also applicable regardless of whether the Project is built in one, two or more phases.