Ocular Hazards from Glint and Glare

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Summary

This document reports the results from the ocular hazard assessment from power tower and heliostats employed by Vast Solar. For the proposed 30MW project at Jemalong NSW, the diffuse glare due to the receiver tubes from all 89 towers provides no significant ocular hazards to nearby points of interest. If viewed as a group, multiple heliostats could potentially produce a temporary after-image however the tracking algorithms and physical obstructions make this scenario unlikely to occur for any observers at ground level.

Introduction

Internationally, concerns have been raised about the potential glint and glare hazards produced by concentrating solar systems [1]. Significant work in this field has been led by Dr. Clifford Ho and colleagues at the Sandia National Laboratories. The calculations presented here are primarily based on their work in modelling these hazards [2].

Two potential sources for glint and glare exist for the 30MW project proposed by Vast Solar: reflections from the heliostat mirror surface and reflected radiation from the receiver on top of the tower. The reflections from the mirrors are considered 'specular' reflections and those from the receiver are considered 'diffuse' reflections.

Sunny periods during the middle of the day present the greatest risk of glint and glare due to the high incident solar flux. Under normal operating conditions, it is expected that the majority of mirrors will target their reflections towards the receiver and therefore not produce glint or glare hazard. Some mirrors may be taken offline and placed in a standby position and therefore the risk for glint and glare has been evaluated in these cases.

During sunny periods a high level of reflected solar flux will hit the receiver tubes surface. Most of the energy is absorbed, however, some of the incident flux is reflected. This reflection can be modelled as a diffuse source radiating evenly in all directions.

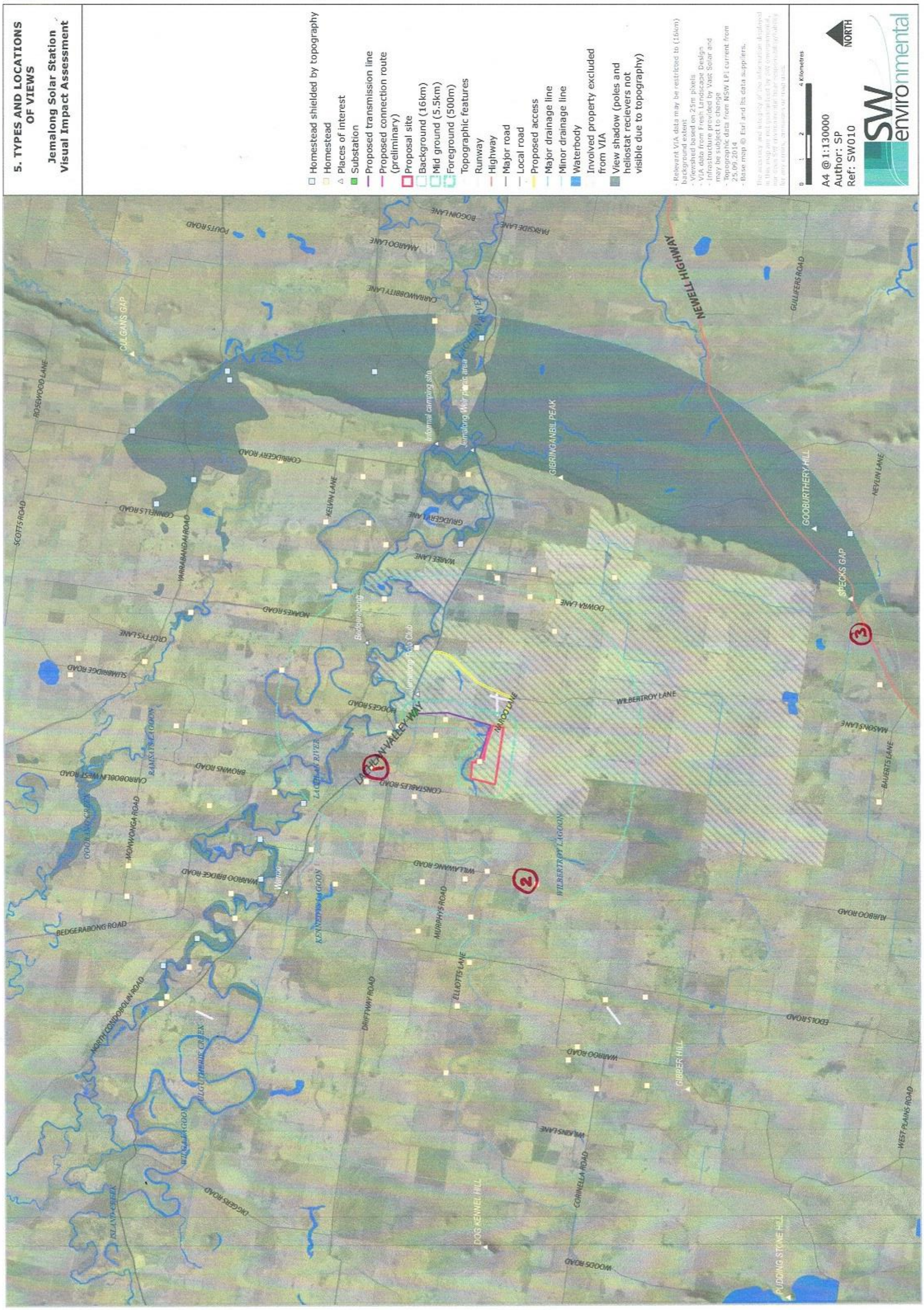


Figure 1 - Approximate viewing locations close to the 30MW site. Location 1 corresponds to Lachlan Valley Way. Location 2 corresponds to the residence on Willawang Rd. Location 3 corresponds to the Newell Highway.

Modelling approach

Eye Damage

Damage to the eye is determined by the intensity of the radiation hitting the retina. Therefore both the flux intensity at the retina, measured in W/cm^2, and the subtended angle of the source are important due the focusing action of the eye lens. The thresholds for temporary and permanent damage adopted in this report are those described in [2]. Temporary damage to the eye, or flash blindness ($E_{r,flash}$), has been shown to occur above the following threshold:

$$E_{r,flash} > \frac{3.59 \times 10^{-5}}{\omega^{1.77}} \; (W/cm^2),$$

which is written in terms of the subtended source angle (ω) in radians. Permanent damage or retinal burn ($E_{r,burn}$) can be expected for irradiation levels above:

$$E_{r,burn} > \frac{0.118}{\omega} for\ \omega < 0.118$$

$$E_{r,burn} > 1\ for\ \omega \geq 0.118.$$

The equations above are represented graphically in Figure 2 on page 5.

Sources of Glare

The calculations in this report relate to the most current field layout, mirror and receiver geometry. There are 89 fields in the 30MW project in a semi-regular grid arrangement (see Appendix Item 4). Each field has 699 heliostat mirrors each with a reflective surface 2.4m x 1.5m in dimension. In regions at a distance much greater than the focal length of the mirrors, heliostats with the longer focal length pose the greatest ocular risk due to the narrow beam angles they produce. Therefore in this report mirrors with the largest expected focal length of 125m are used as a "worst-case scenario" in the following calculations.

Each field contains a receiver consisting of 60 tubes, 25mm in diameter, which results in an irradiated surface with overall dimension of 1.5m x 1.5m. The centre of the irradiated area is 26m above the nominal ground height. The receiver faces south and makes an angle of 20 degrees with the vertical. Shields around the receiver in order to limit spillage and stray reflected light.

The subtended angle for multiple glare sources is taken to be proportional to the square-root of the total area [3].

Observation Locations

It is important to define the viewing location relative to the glare source in order to assess the potential ocular hazard. Three points of interest were suggested by the visual impact consultants for this current investigation. These locations represent two nearby roads, Lachlan Valley Way and the Newell Highway, and the closest residence on Willawang Rd. These locations can be seen on the map in Figure 1 and all are situated at ground level.

The modelling of the glare takes into account the viewing distance and angle. To present a worst case scenario, the modelling provides no consideration for obstructions or atmospheric attenuation of the glare. However, obstructions are discussed below. The distances from each of the points of interest can be seen in Appendix Item 1. These measurements show that the shortest distance to any of the points of interest is 4.16km to Lachlan Valley Way which is approximately due north of the site. This location is susceptible to heliostat reflections, however, due to the orientation of the receiver, glare is not expected from the receiver.

Due to the shielding of glare from the ground level heliostats by the surrounding scrub and trees, the primary concern for glint and glare is due to the receiver on top of the towers rather than the heliostats. This is confirmed through communication with visual impact consultant, Jennie Curtis from Fresh Landscape Design.

Flight Paths

The heliostat array could potentially cause a risk of glare to pilots in aircraft. Both domestic and international commercial flights cruise at an elevation typically greater than 4km. The Forbes aerodrome (YFBS) is the closest public airfield at an approximate distance of 26km (14 nautical miles) in an East-North-East direction from the proposed site. As can be seen in Appendix Item 2, the flight pattern around the aerodrome requires that aircraft approach with a minimum altitude of 0.915km (3000ft) at distances between 14.8 and 27.8 kilometres (8 and 15 nautical miles) from the aerodrome.

The runway at the aerodrome runs in an approximately East-West direction with the approach from the west, as shown in Appendix Item 3. This approach does not come south of Lachlan Valley Way and therefore the minimum expected distance to the pilots eye is similar to that of the viewpoint on that road described above.

Assumptions

Only a small amount of empirical data relating to glint and glare is available for the current mirror and receiver arrangement. As a result the following conservative assumptions have been made based on values for similar systems found in the literature and the arguments presented in the discussion above:

- Heliostat mirrors have a reflectivity (ρ_h) of 0.92
- The receiver tubes have reflectivity of (ρ_r) of 0.5
- Mirrors have an ideal focal length of 125m and zero slope error.
- The maximum solar Direct Normal Irradiation (DNI) is 1000 W/m^2
- The eye of the observer has transmittance (τ) of 0.5, focal length (f) of 0.017m and pupil diameter (d_p) of 0.002m
- The closest viewing point of interest is 4.0km away and has a clear view of the mirrors and receiver.
- The radiative power hitting the receiver is 1.2MW is evenly distributed over the receiver area.
- The receiver produces a diffuse reflection in a hemispherical shape.

Results

A summary of the results from the modelling is shown in Figure 2. The shaded regions represent the different levels of hazard as a function of the subtended angle of the source and the irradiance at the retina. The results are compared to a direct viewing of the sun which has a subtended angle of approximately 9.4mrads at 0.1W/cm^2.

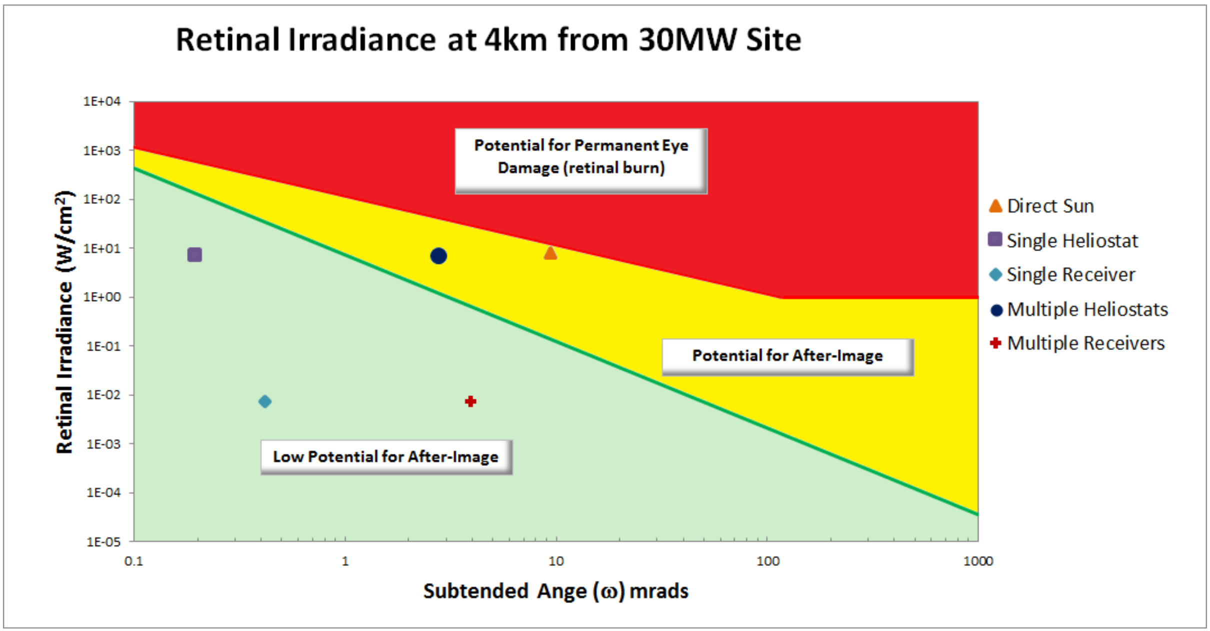


Figure 2 - The results from the modelling the glare from heliostats and receivers at an observation distance of 4km.

Single Heliostat

A single "rogue" heliostat may produce glare to a ground level observer if it is offline or during a tracking procedure. The glare may pass through a gap in surrounding vegetation or obstructions in order to reach the observer.

The glare resulting from the sun reflected from a single heliostat at 4km has low potential to produce an after-image in the eye, as seen in Figure 2. The subtended angle of the heliostat is 0.19 milliradians (mrads). The retinal irradiance is 7.21 W/cm^2.

The minimum distance at which the model predicts low potential for glare from a single heliostat is approximately 900m.

Multiple Heliostats

An observer may receive glare from a cluster of heliostats. This primarily occurs for a group of heliostats that are in a standby state [2]. The current standby algorithm used in the pilot plant focuses the heliostats towards a single point offset to the east of the receiver. Therefore the rays are directed into the sky and would not be observed by an observer on the ground especially when obstructions are taken into account.

Without a completed plant it is difficult to estimate the number of heliostats that will contribute towards glare, however based on the calculations provided in [2], at a distance of 4km less than one heliostat will produce glare at any one time. The results plotted in Figure 2 show the glare hazard expect from 27 heliostats. This number represents the number in a row or column of a single field.

The level of irradiation is similar to viewing the sun however with a reduced subtended angle. A cluster of up to 300 mirrors, or almost half a field, needs to be directly observed at 4km in order to produce a similar level of hazard as looking at an unshielded sun.

Single Receiver

The glare produced by a single receiver when the plant is running at full capacity results in a subtended angle of 0.414 mrads and retinal intensity of 0.007W/cm^2. This combination produces low potential for an after image. No consideration has been given for the viewing angle and therefore this result over estimates the glare risk.

Multiple Receivers

The glare from multiple receivers may be observed from a distant location. It is conceivable that all 89 receivers are viewed at one time forming a glare source with dimension proportional to the square root of the total area. This dimension is used to determine the subtended angle of the source which is 3.905mrads. The retinal irradiance remains the same as a single receiver at 0.007W/cm^2 which produces low potential for an after image.

Consideration for pilots

It would be possible for pilots approaching the Forbes Aerodrome from the West to observe all 89 fields of heliostats. Since the approach is north of the site, there is no possibility to observe the south facing receiver surfaces. The highest potential for glint and glare occurs if all heliostat mirrors in all fields are placed into the standby position. Modelling suggests that at the distances described above, it is possible for only one heliostat from each field to reflect the sun into the eye of an observer at any one time. Therefore, the results presented in this section relate to 89 heliostats forming a combined source of glare. The expected retinal irradiance for an aircraft pilot at 4km is 7.21W/cm^2 at a viewing angle of 5.0mrads which results in “Potential for An After Image”.

Combining the dimension of heliostats presents a worst-case scenario. In reality it is more likely that the glare causing heliostat in each field will form distinct glare source on the retina, which reduces the viewing angle and as a result the risk of glint and glare.

Tower Illuminance Model

The results presented here are confirmed by those supplied by the Tower Illuminance Model (TIM) online tool. This tool is currently in development by Sandia National Laboratories however, it reinforces the results of the prior heliostat modelling, as can be seen in Figure 3 below.

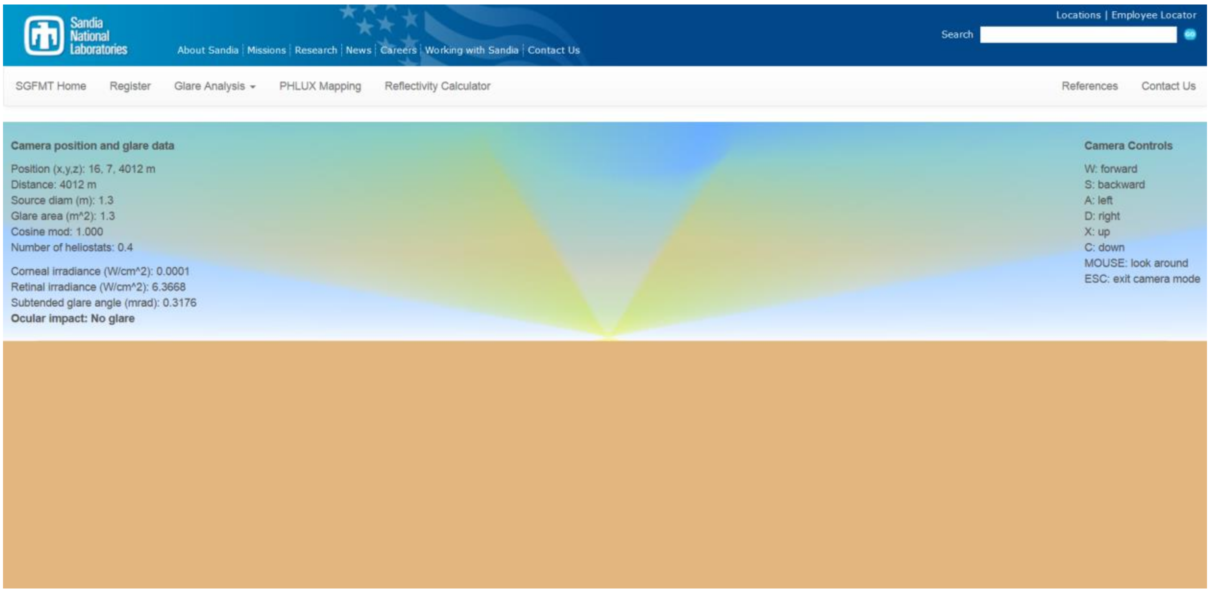


Figure 3 - Results from the Tower Illuminance Model for a single field in the 30MW project.

Conclusion

The analytical results presented in this report demonstrate that from a distance of 4km, neither the combined receivers nor a single “rogue” heliostat pose any significant risk of glare. It is possible for a collection of heliostats to produce a hazard resulting in an after-image at a distance of 4km. The scenarios modelled in this report represent the condition that all heliostats are placed in the standby position and a single heliostat form each field merge to form a combined source of glare. During normal operation, especially in times of high solar energy, it is expected that the heliostats will very rarely all be in this state. More probable is that a few fields of heliostats may be in standby for maintenance and which reduces the risk to that of a single heliostat. In all the cases modelled, even with the conservative assumptions applied, the predicted potential for the after-image is no stronger than a direct viewing of the sun.

Should the risks be of concern in the future, there are mitigation measures which are currently being investigated by Vast Solar. One such measure that has shown to be effective in overseas examples is staggering the location of the standby target in order to minimise the potential for glare from a cluster of heliostats.

The results from the modelling presented in this report require further validation once the pilot plant is complete. This may be undertaken with the Empirical Glare Analysis Tool provided online by Sandia National Laboratories [4]. This tool requires photographs to be taken of glint and glare sources and the sun in order to compare relative brightness.

References

[1] S. Barret, “Glare Factor: Solar Instalations and Airports,” Sandia National Laboratories, [Online]. Available: http://solarindustrymag.com/issues/SI1306/FEAT_02_Glare_Factor.html. [Accessed 3 2 2015].

[2] C. K. Ho, C. M. Chanbari and R. B. Diver, “Methodology to Assess Potential Glint and Glare Hazzards from Concentrating Solar Power Plants: Analytical Models and Experimental Validation,” in *ES2010*, Phoenix, Arizona, USA, 2010.

[3] C. K. Ho, C. A. Sims and J. M. Christian, “Evaluation of Glare at the Ivanpah Solar Electric Generating System,” Sandia National Laboratories, Albuquerque, New Mexico, 2014.

[4] C. A. Sims, “Solar Glare and Flux Mapping,” Sandia National Laboratories, [Online]. Available: https://share.sandia.gov/phlux. [Accessed 3 02 2015].

Appendices

Item 1

Minimum distances from the 30MW site to the points of interest for the glint and glare analysis.

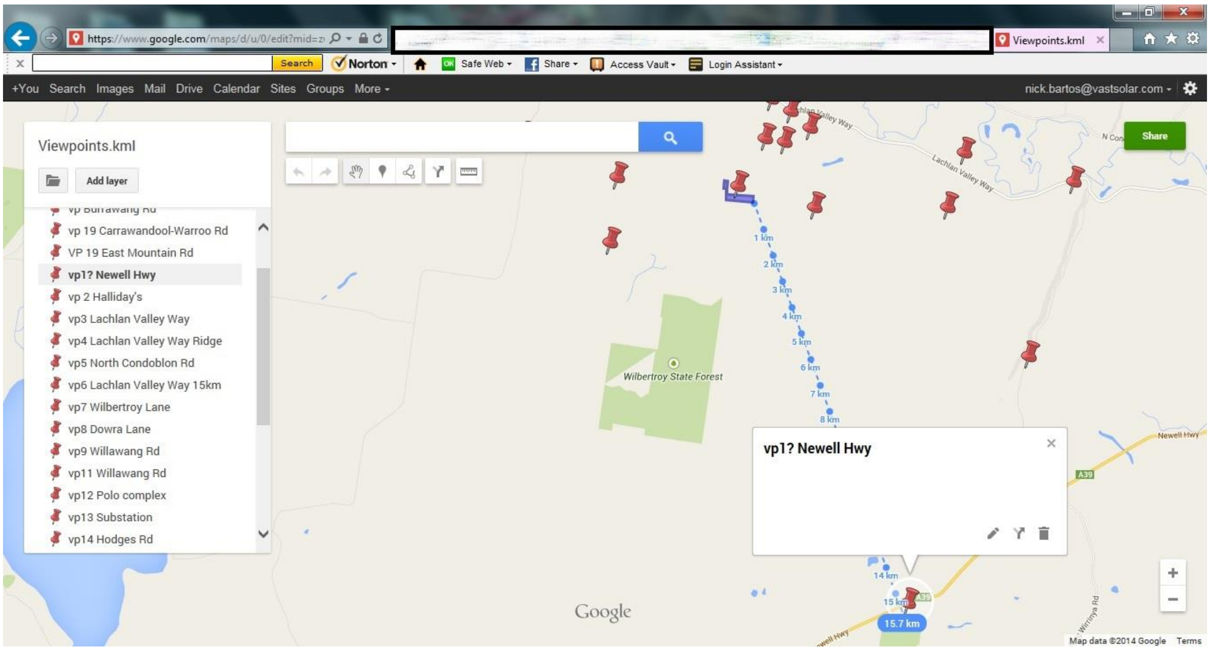


Figure 4 - Distance to Viewpoint 1 of 15.7km as measured using Google Maps.

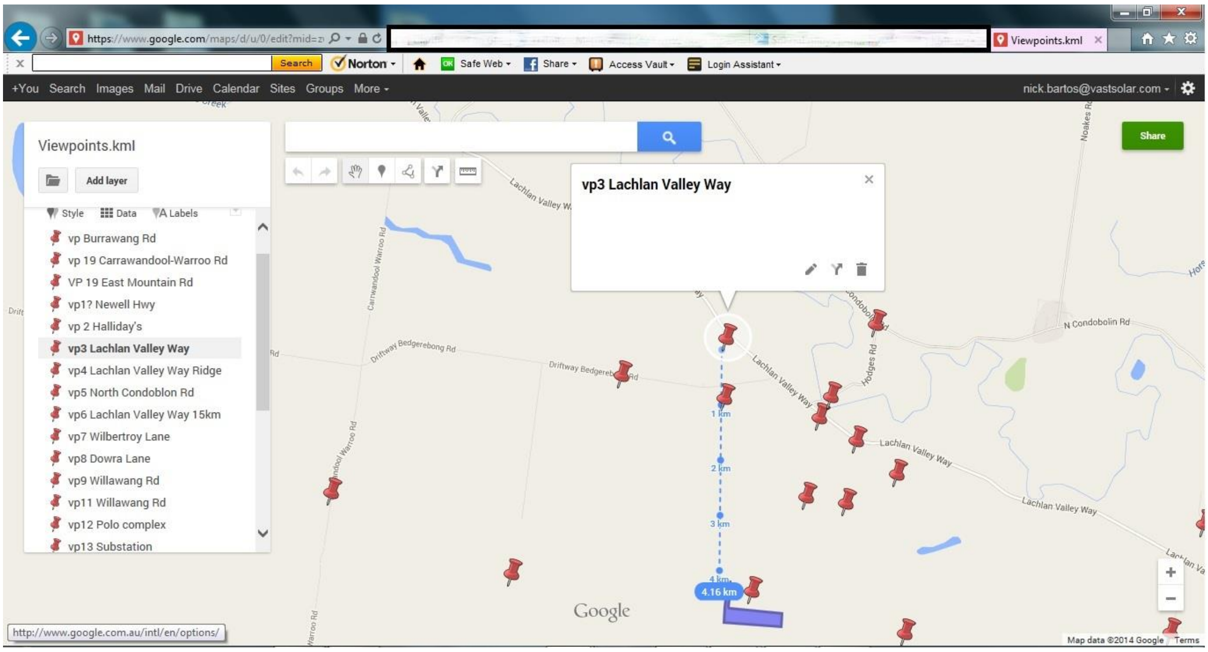


Figure 5 - Distance to Viewpoint 3 of 4.16km as measured using Google Maps.

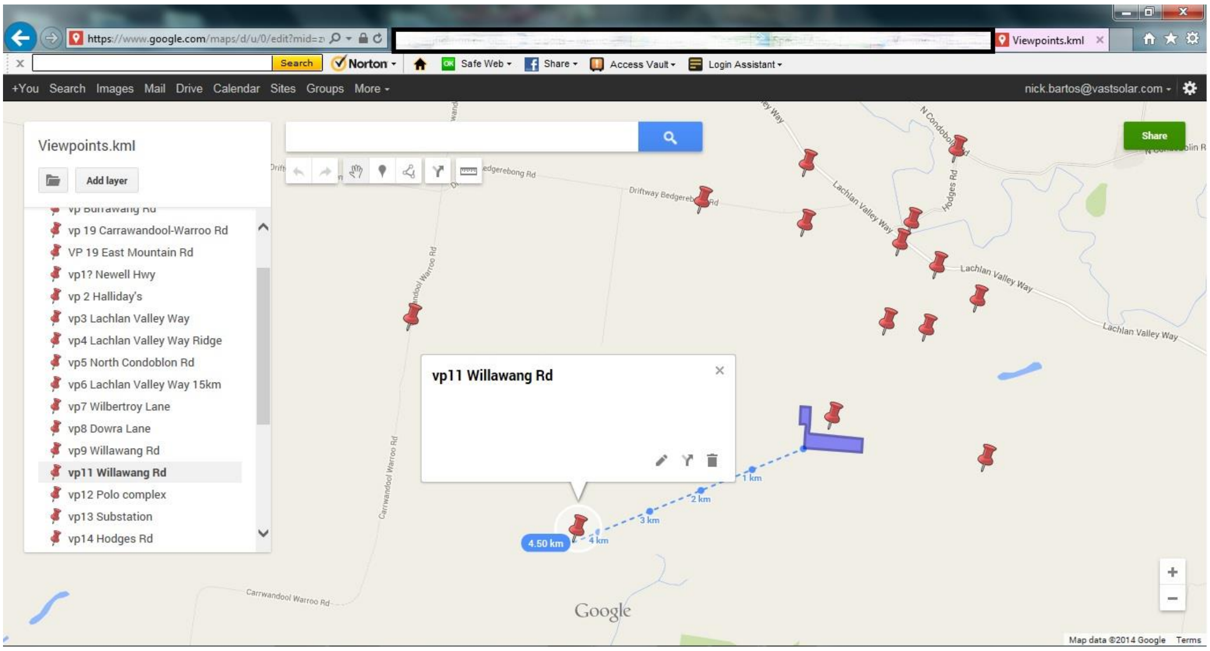


Figure 6 - Distance to Viewpoint 11 of 4.5km as measured using Google Maps.

Item 2

Permitted flight patterns around the Forbes Aerodrome.

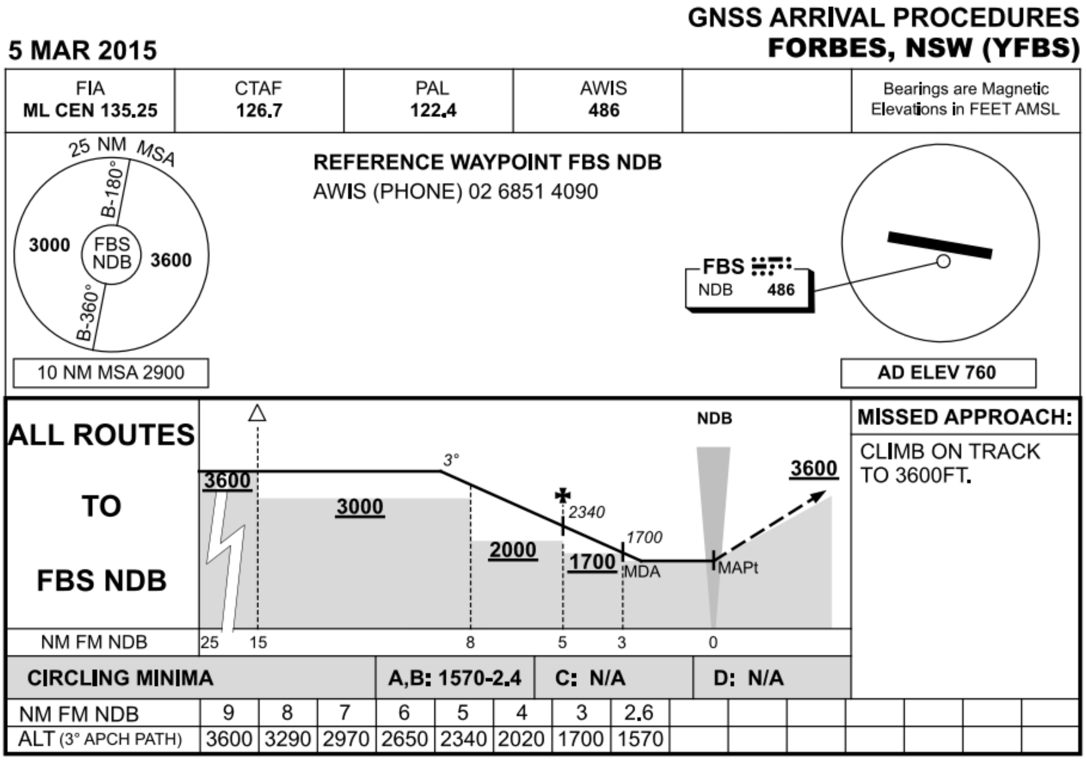


Figure 7 - Forbes aerodrome arrival procedures, Airservices Australia 2015. Note all elevations are in feet and distances in Nautical Miles. (1000ft is 0.305 kilometres and 1NM is 1.852 kilometres)

Item 3

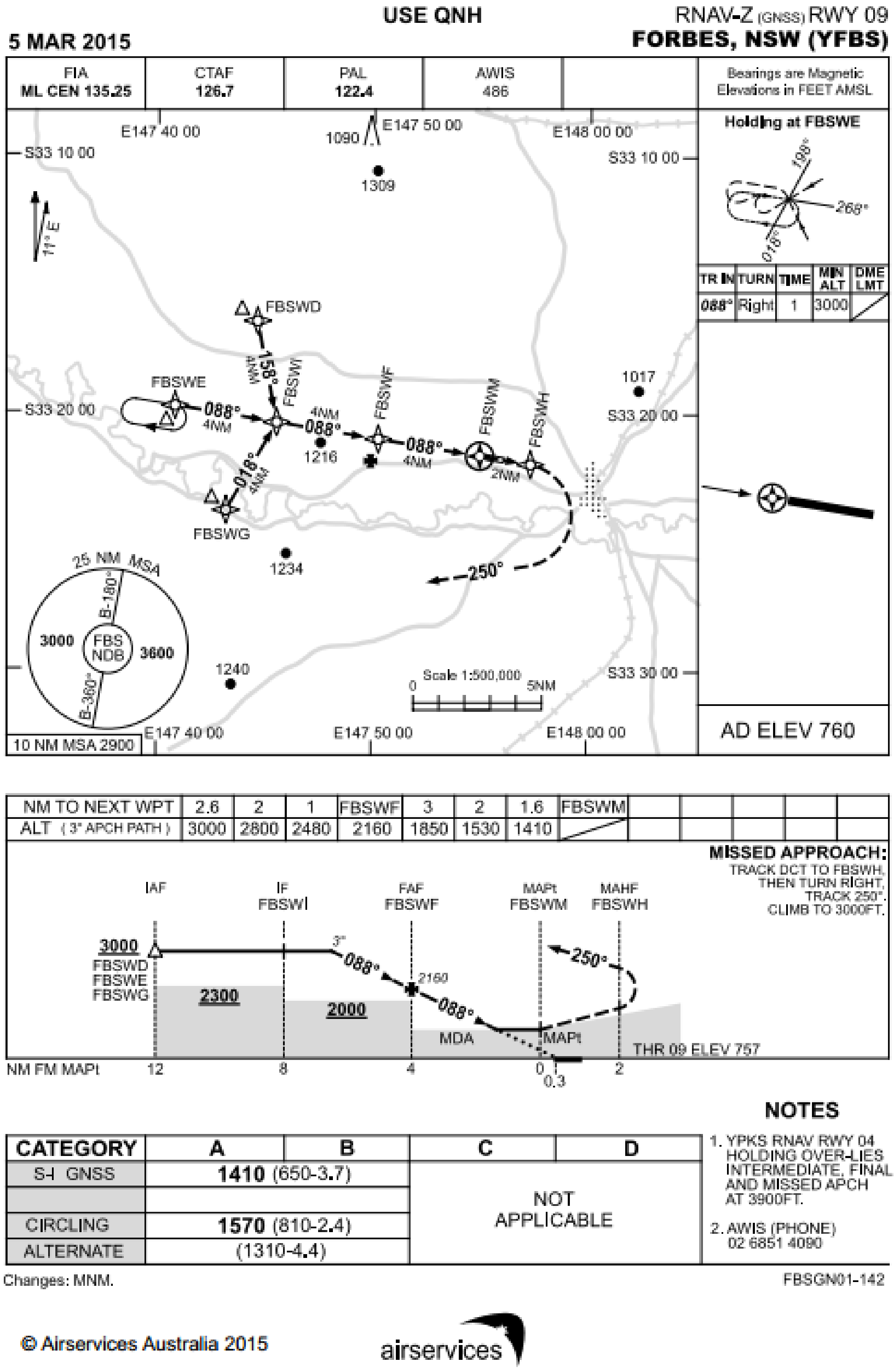
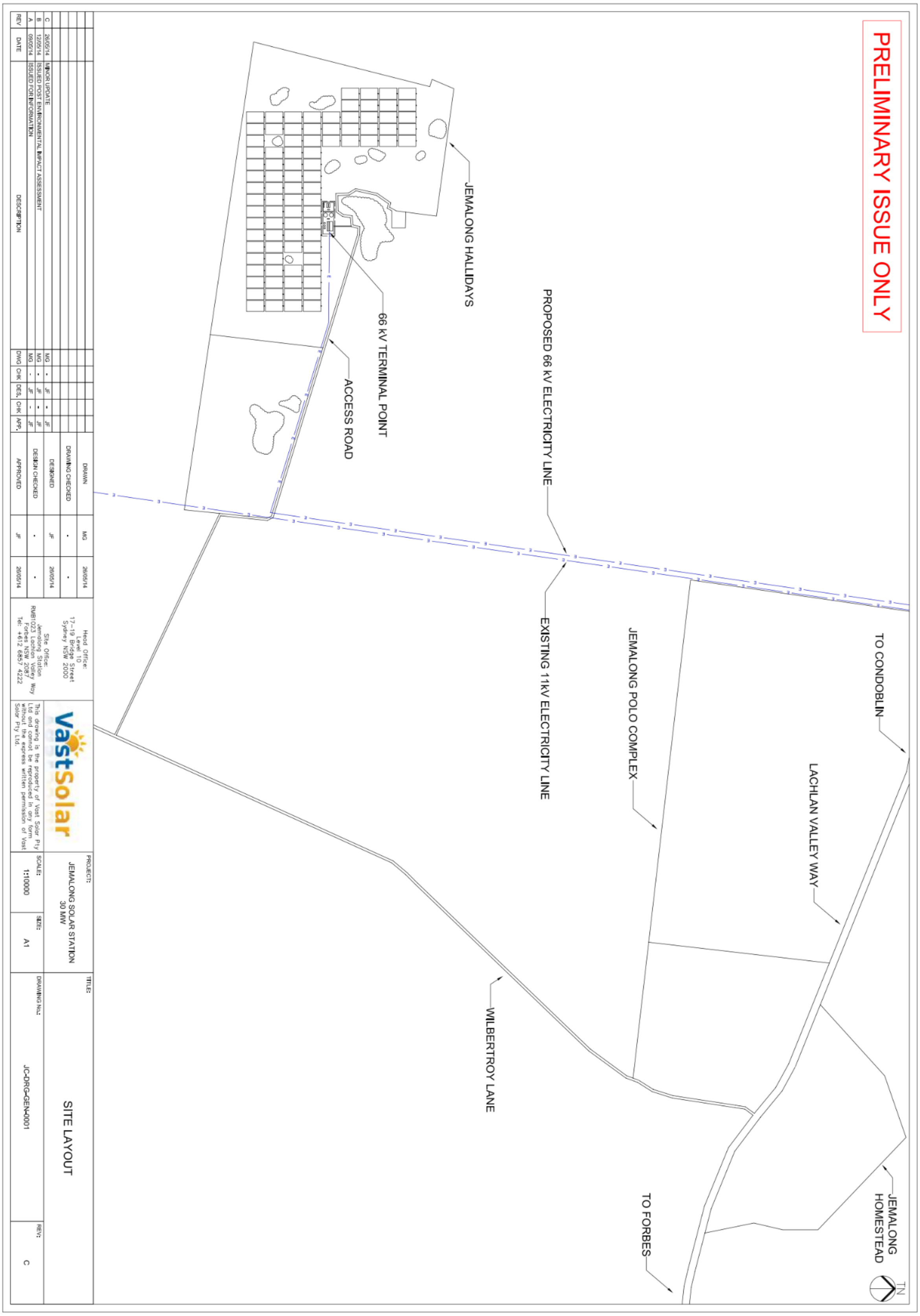


Figure 8 - Approach to Forbes Aerodrome from the West.

Item 4

Proposed 30MW site at Jemalong, NSW showing the grid of heliostat fields.



Item 5

Spreadsheet used to obtain results of glare analysis above. Values in orange represent calculated values.

DATA INPUTS

Sun			
Solar Radiation	DNI	0.1	W/cm2
Subtended Angle	beta	9.4	mrads
Retinal Irradiance	Ersun	**7.83**	W/cm2
Heliostat			
Reflectivity	rho_h	0.92	
Focal Length	b	125	m
Area	Ah	3.6	m2
Nominal Diameter	Dh	**2.1**	m
Number of Heliostats	nh	27	
Slope Error	Berr	0	mrads
Receiver			
Tube Diameter	Dt	0.0254	m
Tube Length	Lt	1.5	m
Number of tubes	nt	60	
Angle relative to vertical	phi	20	degrees
Centre Height	Hr	26	m
Reflectivity	rho_r	0.5	
Diffuse Area	Ad	**7.2**	m2
Source Area	As	**2.3**	m2
Pd	Pd	**600000**	W
Number of Receivers	nr	89	
Eye			
Distance	x	4	km
Transmission Coef	tau	0.5	
Focal Length	f	0.017	m
Pupil diameter	dp	0.002	m
Radial Distance	rd	**4000.1**	m

RESULTS			
Specular Heliostat			
Corneal Irradiance	Ec_h	0.000039	W/cm2
Retinal Irradiance	Er_h	7.21	W/cm2
wspot	wspot_h	0.194	mrad
Heliostat Burn Level	Er_burn_h	609.61	W/cm^2
Heliostat Flash Level	Er_flash_h	134.1	W/cm^2
Heliostat Hazard Rating	HAZ_h	Low-potential for After-Image	
Multiple Heliostats			
Corneal Irradiance	Ec_hm	0.000039	W/cm2
Retinal Irradiance	Er_hm	7.21	W/cm2
wspot	wspot_hm	2.8	mrad
Heliostat Burn Level	Er_burn_hm	42.43	W/cm^2
Heliostat Flashe Level	Er_flash_hm	1.19898	W/cm^2
Heliostat Hazard Rating	HAZ_hm	Potential for After-Image	
Diffuse Receiver			
Retinal Irradiance	Er_r	0.007	W/cm2
Subtended angle	wspot_r	0.414	mrad
Receiver Burn Level	Er_burn_r	285.07	W/cm^2
Heliostat Flashe Level	Er_flash_r	34.9	W/cm^2
Heliostat Hazard Rating	HAZ_r	Low-potential for After-Image	
Multiple Receivers			
Retinal Irradiance	Er_rm	0.007	W/cm2
Subtended angle	wspot_rm	3.905	mrad
Receiver Burn Level	Er_burn_rm	30.22	W/cm^2
Heliostat Flashe Level	Er_flash_rm	34.9	W/cm^2
Heliostat Hazard Rating	HAZ_rm	Low-potential for After-Image	