ABENGOA SOLAR LLC

MST Heliostat Final Project Report

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MST Heliostat Final Project Report

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1 Specifications

Molten Salt Tower heliostat brainstorming and specifications development began in May 2012. Overall optical and structural performance specifications are those of the Sunshot goal and are similar to Abengoa design criteria:

Table 1 MST heliostat design requirements

Beam error under 5 m/s winds	≤ 3 mrad
Beam error under windy conditions (12 m/s)	≤ 4 mrad
Wind speed at which to go to stow	≥ 15.6 m/s
Wind speed at which heliostat must survive in any orientation	≥ 22.4 m/s
Wind speed heliostat must survive in stow orientation	≥ 40 m/s
Lifetime	≥ 30 years
Cost	≤ 120 $/m^2 (≤ 220 $/kWth with MST project assumptions)

All winds speeds above are 3 second-average gusts and measured at 10 m height.

The optical requirements are stringent. Prior to brainstorming heliostat designs, a rough optical error budget for the heliostat field was created and is summarized below.

Table 2 MST Optical error budget guideline

	5 m/s wind loading		12 m/s wind loading	
Beam error type	Isolated (mrad)	**Field average (mrad)**	Isolated (mrad)	**Field average (mrad)**
Reflector	2	**2**	2	**2**
Structure deflection	1	**0.3**	4	**1.3**
Assembly	1	**1**	1	**1**
Tracking	1.5	**1.5**	1.5	**1.5**
Other	1	**1**	1	**1**
Convolved total:	3.0	**2.9**	4.9	**3.2**

Optical errors are presented as beam errors, i.e. 2x slope and pointing errors. Error budgets at two wind speeds, 5 m/s (11 mph) and 12 m/s (27 mph), are presented for "isolated" and "field average" heliostat values. 5 m/s is the DNI weighted wind speed at the Nevada design site, while 12 m/s wind speed is the maximum wind speed at which the heliostat must maintain optical accuracy. The "isolated" heliostat error budget reflects structural deflection values associated with worst-case orientation and wind-loading, while the "field average" represents the average structural deflection for the heliostat field over the course of the year due to average orientation and wind loading. The field average is used in annual performance models. The heliostat was designed to meet isolated heliostat requirements, and then its field average value was approximated from it.

The values shown in the optical error budget table were a guide, with the understanding that the value associated with each line item should not be regarded as "set-in-stone" though the convolved field average totals, both near 3 mrad, should be according to present performance standards.

Wind loading was calculated using the methodology described by Peterka[1] to determine the required stiffness of structural members and torques of the drives.

2 Brainstorming and downselect

Brainstorming began once the specifications were in place. Designs from the brainstorming were compared on a $/m^2 basis using costing rules-of-thumb, experience, and vendor quotes. If it was believed that a design would offer better (or worse) optical performance than specified, an annual plant performance model was used to translate the change in performance into a $/m^2 benefit or disadvantage.

Figure 1 illustrates and describes the five most promising designs from the brainstorming process that were the subject of the downselect in December 2012. It was believed that optical performance would be similar for these designs.

The five heliostats range in size from 15 m^2 to 200 m^2 with installed costs from 97 to 108 $/m^2. Their cost is compared to a baseline Sandia National Laboratory stretched membrane heliostat. Low cost enablers for the larger heliostats were hydraulic drives, efficient support structures, and the large reflection area possible with minimal material using a stretched membrane design, while cost enablers for the small heliostats were recent reductions in control and motor costs, the use of PV panels and batteries for power instead of conventional field wiring, and the reduction in structure due to reduced wind loading on a per square meter basis. Thus, both approaches were viable for reaching the cost target.

The purpose of the downselect was to pick one design for further development. Though it was agreed that $/m^2 was the most important evaluation metric, the cost of the five heliostats were similar within our ability to accurately assess cost at this stage. The next criteria was risk. Large heliostat designs tend to rely heavily on field labor, and field labor costs can vary from $20/hr to $180/hr depending on location and specialty. This was determined to be a large risk, especially in markets like the USA with higher

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[1] Peterka, J.A., Derickson, R.G. *Wind Load Design Methods for Ground-Based Heliostats and Parabolic Dish Collectors*, New Mexico : Sandia National Laboratories, 1992. Sandia Report SAND92-7009

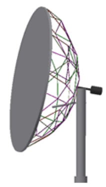
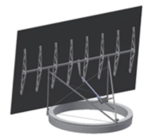
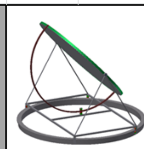
Component	Baseline 140 m² heliostat Cost	 150 m² Heliodesic double stretched membrane on a pedestal with hydraulic cylinder drives		 36 m² Rioglass panels (8) on pre-cast concrete ring ballast foundation with electromechanical drives		 18 m² Rioglass panels (4) on pre-cast concrete ring ballast foundation with electromechanical drives		 15 m² single, flat stretched membrane on pre-cast concrete ring ballast foundation with electromechanical drives		 200 m² double stretched membrane supported by truss ring and carousel driven by rotary hydraulic drives, with concrete pylon foundations	
Heliostat Cost	**$/m²**	**Cost**	**+/- to BL**	**Cost**	**+/- to BL**	**Cost**	**+/- to BL**	**Cost**	**+/- to BL**	**Cost**	**+/- to BL**
Azimuthal Drive	$28.37	$6.50	-$21.88	$9.22	-$19.15	$10.50	-$17.87	$12.38	-$15.99	$4.00	-$24.37
Support Structure	$23.73	$12.94	-$10.79	$12.37	-$11.37	$7.47	-$16.26	$0.00	-$23.73	$14.23	-$9.50
Heliostat Structure	$27.08	$13.64	-$13.44	$7.31	-$19.76	$5.43	-$21.65	$15.07	-$12.01	$0.00	-$27.08
Membranes	$17.53	$12.80	-$4.73	$0.00	-$17.53	$0.00	-$17.53	$5.00	-$12.53	$12.93	-$4.61
Focus System	$13.68	$6.00	-$7.68	$0.00	-$13.68	$0.00	-$13.68	$0.00	-$13.68	$7.00	-$6.68
Mirror	$11.27	$10.18	-$1.09	$35.00	$23.73	$35.00	$23.73	$15.50	$4.23	$7.50	-$3.77
Elevation Drive	$9.45	$6.50	-$2.96	$11.61	$2.16	$9.79	$0.34	$11.76	$2.31	$7.20	-$2.25
Field Wiring	$8.71	$2.78	-$5.93	$4.92	-$3.79	$6.80	-$1.91	$7.00	-$1.71	$2.39	-$6.32
Ring	$6.80	$4.32	-$2.48	$0.00	-$6.80	$0.00	-$6.80	$11.07	$4.27	$9.68	$2.88
Labor	$5.12	$5.12	$0.00	$5.12	$0.00	$5.12	$0.00	$5.12	$0.00	$5.12	$0.00
Field Assembly	$2.63	$2.63	$0.00	$2.63	$0.00	$2.63	$0.00	$2.63	$0.00	$2.63	$0.00
Foundation	$2.60	$5.57	$2.97	$14.17	$11.57	$12.89	$10.29	$14.54	$11.94	$15.75	$13.15
Drive Electrical	$2.02	$0.00	-$2.02	$0.00	-$2.02	$0.00	-$2.02	$0.00	-$2.02	$0.00	-$2.02
Controls	$1.94	$7.47	$5.53	$2.00	$0.06	$3.07	$1.13	$3.50	$1.56	$5.75	$3.81
Tooling	$1.58	$1.58	$0.00	$1.58	$0.00	$1.58	$0.00	$1.58	$0.00	$1.58	$0.00
Feedback	$2.58	$1.95	-$0.63	$1.31	-$1.27	$2.70	$0.12	$2.70	$0.12	$1.15	-$1.43
Total Capital Cost	**$165.10**	**$99.97**	**-$65.13**	**$107.25**	**-$57.85**	**$102.98**	**-$62.12**	**$107.85**	**-$57.25**	**$96.91**	**-$68.20**

Figure 1 Downselect options as of December 2012

labor rates. In the case of the smaller heliostats, the cost on a $/m^2 basis depends more on the cost of all the different components that make up the heliostat (drives, control, power, structure) and if any one component is significantly more expensive than projected, it can eliminate the potential savings relative to the baseline quickly.

Multiple vendor bids associated with cost-sensitive components (such as the controller and drives) as well as perceived automated manufacturing advantages associated with a smaller heliostat led to its selection in the end. At the smaller size, the stretched membrane did not have a cost advantage relative to the composite facet, and so for lower risk and commercial relevance the 18 m^2 composite facet heliostat was selected.

This heliostat, named the ROP 18, is the subject of the remainder of this report. At Abengoa Solar, this development process has been perceived as successful and steps are being taken to commercialize it. The Abengoa Solar heliostat development team wishes to thank DOE for their support and critical review of this task.

3 Design development

3.1 Structure

The heliostat had to meet strength (stress) and deflection (optical error) criteria. Strength criteria means that stresses in the structural members should not exceed a predetermined stress based on material properties, geometry, and desired safety factors. The deflection criterion corresponds to maximum structural deflections that translate to angular deviations that affect the direction of the reflected beam towards the receiver. Finite-Element-Analysis (FEA) was used to assess both for candidate heliostat structures undergoing various wind loading scenarios.

Early in the analysis it became clear that acceptable structural deflection associated with 12 m/s wind gusts incident on a heliostat structure with its facet array pointed 30° from zenith was going to be the most difficult design criterion to meet, and would therefore dictate the design of the structure and the size of its members. The structure changed little-by-little to meet it, and a snapshot showing some aspects of the progress is shown in Figure 2. At the end of the design process, the amount of structural steel in the heliostat was compared to the to the Sandia[2] semi-empirical analysis that relates the amount of structural steel per square meter of the heliostat to its area. This comparison is shown in Figure 3, along with data from other heliostats.

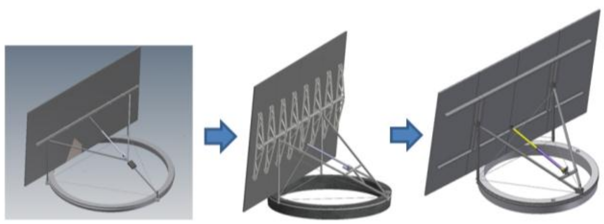


Figure 2 MST heliostat design progression

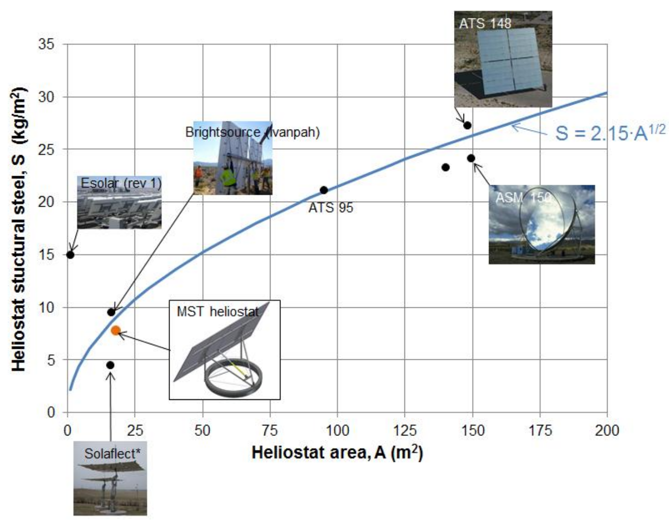


Figure 3 Comparison of the amount of structural steel in the MST heliostat compared to Sandia's structural steel curve, with other heliostats for reference

[2] Kolb, G.J., Jones, S.A., Donnnelly, M.W., Gorman, D., Thomas, R., Davenport, R., Lumia, R., *Heliostat Cost Reduction Study*, New Mexico : Sandia National Laboratories, 2007. Sandia Report SAND2007-3293

3.2 Concrete ring

The concrete ballast foundation serves multiple purposes: prevention of motion under significant wind loading, ease of installation, structural enhancement through the enablement of a tensioned steel structure, and drive cost reduction through gear reduction. For it to fill these functions, however, it had to pass some strict shape and deflection criteria.

An accurate roll-formed form for the concrete was procured by Lindsay Precast, as was a roll-formed V steel track. After the pour the shape of both was inspected by photogrammetry. The track radius varied by ± 2.0 mm (± 0.080 in) to 95% confidence, while the concrete radius varied by ± 1.0 mm (± 0.040 in). Both were within specification, though prototyping efforts continue to attempt to reduce the variation in the track radius as this influences the required excursion of the tension rods in the ROP structure.

Also of interest was potential deflection of the concrete ring and embedded track due to non-uniform ground support. In a field installation, it is envisioned that the concrete ring will be placed on the ground quickly with little-to-no ground preparation. The ring may just be supported by three unevenly spaced points. If the ring and track deflect, then an angular error may result, especially in elevation.

The shape of the track as a function of support was investigated using photogrammetry. Figure 5 shows three support conditions - ground supported, evenly on 3 points, and support on 2 ends - where the shape of the ring and track were quantified.

Figure 4 Photogrammetric evaluation of concrete ring and track deflection as a function of support condition

Vertical deviations in the track cause an angular error, mostly in elevation, of the reflected beam. Figure 5 quantifies the deviation relative to the ground supported case. The maximum deviation would result in an angular error of approximately 0.4 mrad, which is a small overall contributor in the error budget and therefore acceptable.

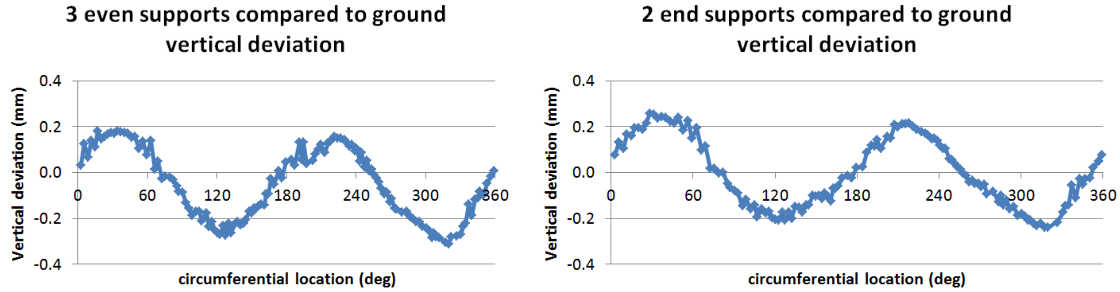


Figure 5 Vertical deviation of track relative to the ground supported base case for 3 and 2 point support cases

3.3 Azimuth drive

Early simulation work suggested that wind loading would cause enough contact stress and wear between the wheels and the concrete that a steel-on-steel interface was required. Steel wheels and a steel track were selected for testing. A succession of tests were carried out: coefficient of friction, accuracy, and wheel wear. Overviews of each are presented below.

3.3.1 Coefficient of friction

Figure 6 shows how the coefficient of friction between the steel wheel and track varied as a function of loading, but most importantly, track soiling condition.

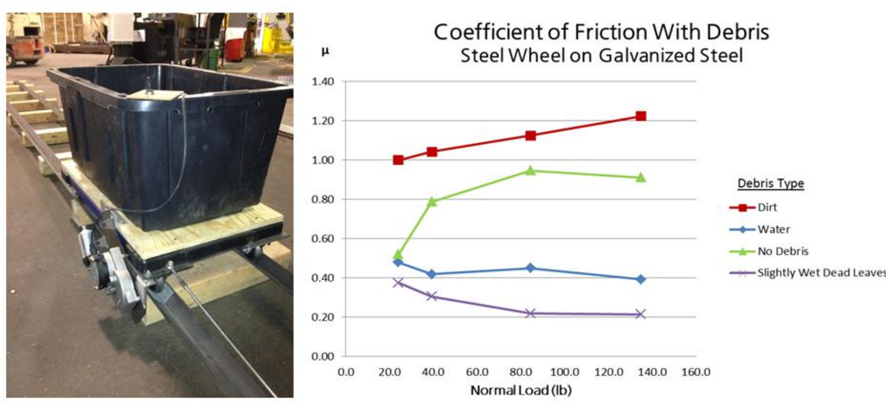


Figure 6 Coefficient of friction testing between drive wheel and track

3.3.2 Accuracy

The challenge of obtaining accurate tracking from cheap, inaccurately manufactured components was foremost on the project team's mind from the beginning. For astronomical telescopes and robotics, friction drives are common because they offer gear reduction, are energy efficient, have no backlash, and require only controlled radii for accuracy. The ROP's small radius steel wheel operating on the large radius roll-formed steel V-track supported by the concrete ring is a friction drive.

Figure 7 Testing of azimuth track friction drive showing proximity sensor and laser-cut encoder

Even so, there was a concern that wheel slippage on the track, or a drive wheel radius that varies with time, would require some form of error-correction in the azimuth track. Therefore a strip with laser cut holes was manufactured and envisioned to be a large radius encoder whose edges are detected by an inductive sensor. The assembly is show in Figure 7.

ISO 230-2[3] was selected as the methodology to determine the accuracy of the drives. In this method, 5 target positions are approached in both forward and backward directions. Each time a target position is reached, its location relative to a reference position is measured externally (in this case, by laser radar) and compared to the programmed target distance. As described by the standard, the accuracy can be summarized as a function of the deviations between the true external reference and the programmed set point. An example of the application of this test standard to a candidate azimuth drive is shown in Figure 8. An accuracy of ± 1.5 mm at 95% confidence on the test track corresponds to an acceptable azimuth beam tracking

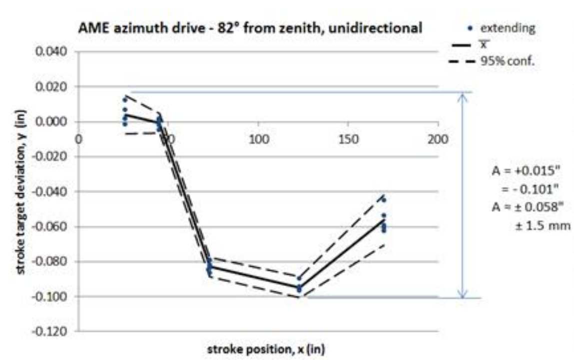
82° from zenith: 4519 N (1016 lb) Avg. rod tension: 5720 N (1286 lb) Avg. DC power: 6.7 W Accuracy: ± 1.5 mm		

Figure 8 -Unidirectional accuracy test of azimuth drive in the laboratory

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[3] "Test code for machine tools – Part 2: Determination of accuracy and repeatability of positioning numerically controlled axes", ISO 230-2-2006(E), Third Edition, 2006-03-15, International Organization for Standardization, Geneva, Switzerland.

accuracy of ± 1 mrad on the heliostat considering the geometric gear reduction.

3.3.3 Wear

It was theorized that the large normal force between the wheel and the track would cause the drive wheel to wear, but the rate of the wear far exceeded calculations. After the accuracy testing, the azimuth track was put through 24 hour, 5 day/week continuous duty cycling to simulate "years" of typical operation. Testing was stopped after 2 months, the equivalent of 20 years. Figure 9 shows how the profile of the drive wheel changed with time.

The reason for the fast wear rate was determined to be a slightly non-orthogonal drive axis relative to the planar axis of the steel track. This misalignment causes the wheel to attempt to ride up or down the track, depending on direction. This misalignment is invisible to the eye and will be an obvious result of typical manufacturing. The heliostat presently uses the "year 8" profile to start, as the rate of wear from this point on is reduced.

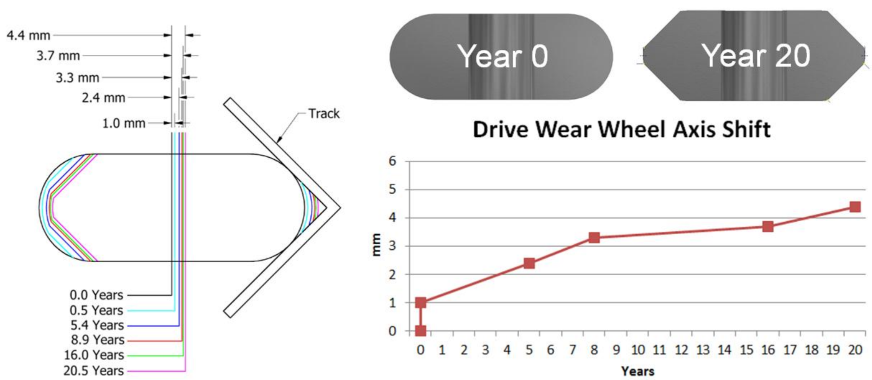


Figure 9 The changing profile of the steel drive wheel with lifecycle testing

3.4 Elevation drive

The linear actuators from several prospective vendors were evaluated based on the aforementioned ISO accuracy test. An indoor test stand was constructed and the actuators were tested in turn (Figure 10).

Figure 10 Elevation drive indoor test stand

Figure 11 shows the results of the most promising actuator, custom developed by AME, and compares its results to two other commercial actuators. The accuracy of ± 0.4 mm to 95% confidence equates to an elevation beam tracking error of ± 0.8 mrad, which is within specification for the drive. Of the other actuators, the Schaeffler actuator could have also met specification if its uniform lead screw error could have been calibrated out, however its projected cost was near double that of the AME drive. The Joyce Dayton actuator is used in tracking PV systems and was not expected to perform well in the tests.

For both Azimuth and Elevation drives, AM Equipment (http://www.amequipment.com) was selected based on performance and projected commercial cost to provide drives for the ROP. This company specializes in high volume manufacturing and supply of brushed DC motors to the automotive industry, and they were eager to apply their manufacturing and design expertise to a new application.

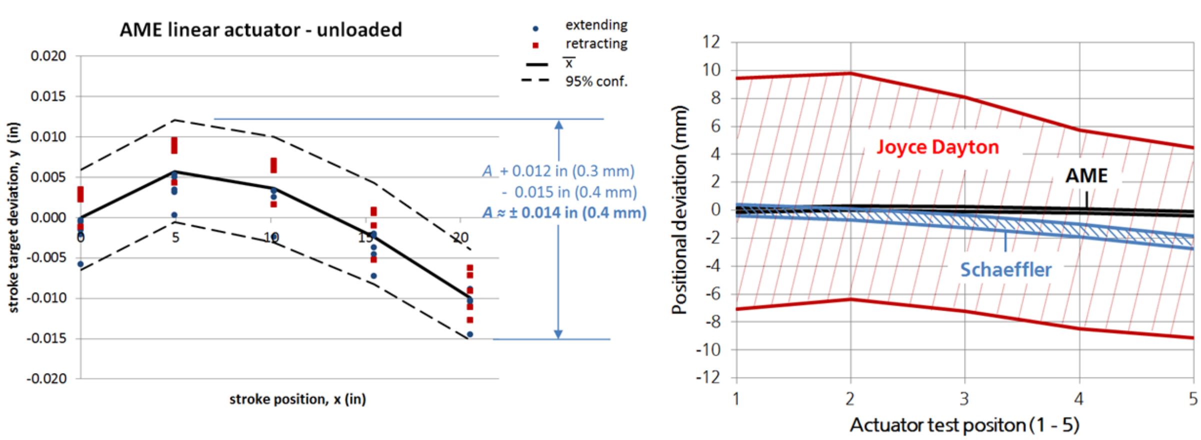


Figure 11 Accuracy testing of prospective linear actuators

Like the azimuth drive, the elevation drive was also subjected to life cycle testing. Its accuracy was within specification until year 20. Work continues to ready this drive for commercial application.

3.5 Prototype construction and deployment

With component evaluation complete, a design for the structure, and control hardware and algorithms demonstrated, the first ROP prototype was assembled and deployed at SolarTac at the end of 2013. Pictures of the assembly are shown below.

Figure 12 Construction of the first prototype

The heliostat was put on-sun successfully for the first time in February 2014.

Figure 13 ROP tracking the sun on to the beam characterization target

3.6 Tracking

Though Figure 13 shows the beam centered on the target, initial tracking was not so successful. However, a calibration method described by Guo[4] was adapted to the ROP geometry. Subsequent tracking showed that the orientation of the heliostat and many of its inherent optical misalignments can be determined from deviations of the beam centroid from the target, and then corrected for by the tracking algorithm, as shown below.

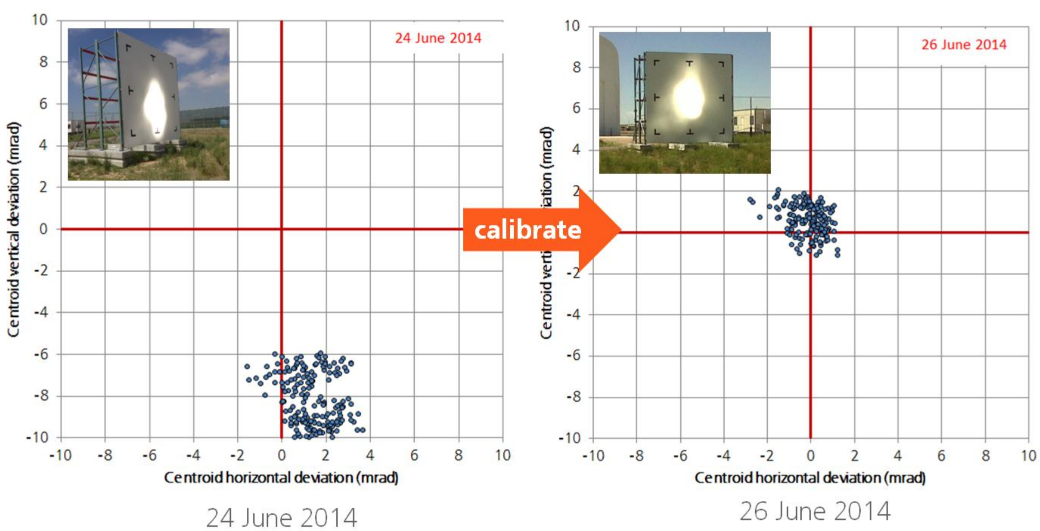


Figure 14 ROP tracking, before and after calibration. Points indicate beam centroid at 1 minute intervals.

[4] Guo, M. et al. "Determination of the angular parameters in the general altitude-azimuth tracking angle formulas for a heliostat with a mirror-pivot offset based on experimental tracking data," Solar Energy 86 (2012) pp 941-950.

To quantify the accuracy of tracking, circles indicating 1σ and 2σ confidence intervals are overlaid on the after-calibration tracking data. Recall from Table 2 that the allowable 1σ tracking error budget was 1.5 mrad. Figure 15 shows a tracking accuracy of 1.3 mrad, which is within specification.

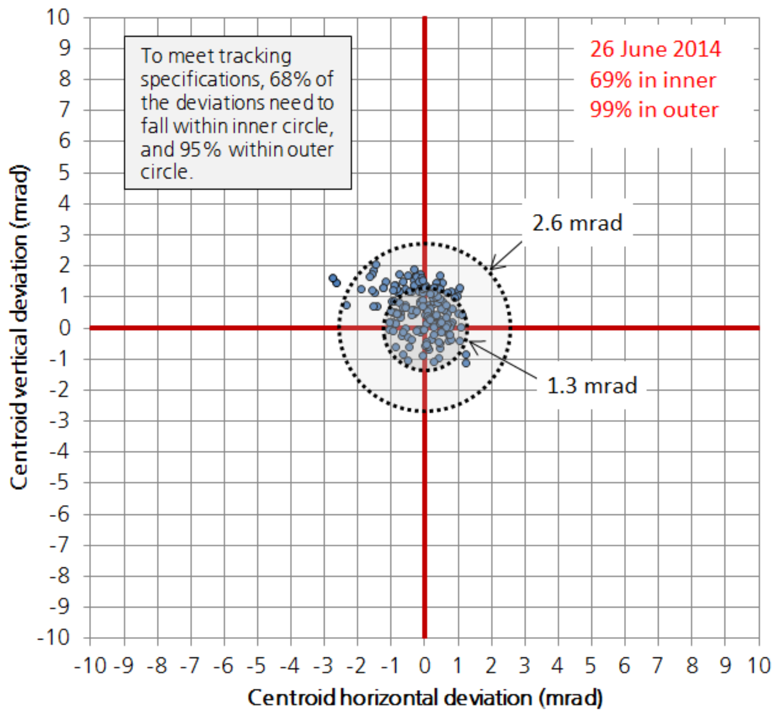
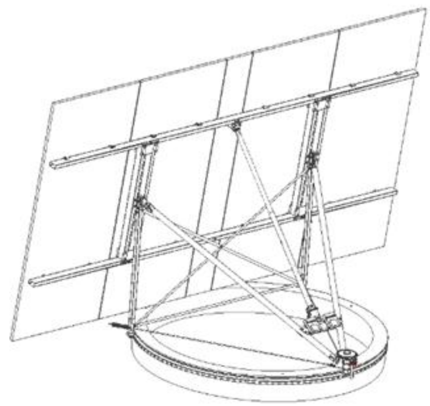


Figure 15 Tracking accuracy of the ROP

3.7 Commercial cost estimate

A 100 MWe plant with 6 hours of thermal energy storage will require about 60,000 ROP heliostats. Vendors quotes were based on this volume, often with significant discounts relative to single unit prices. Abengoa Research - Consulting performed the assembly, installation, and manufacturing study, leveraging knowledge gained through their involvement in SolarMat. Figure 16 describes the heliostat cost as a function of material costs and assembly and installation costs. The installed heliostat cost in Nevada is projected to be 114 $/m^2$. This is less than the 120 $/m^2$ project goal.

Qty	Description	$/heliostat	$/m^2
1	ROP Heliostat, materials, 18m^2	$1,809.04	$100.64
1	Concrete and Track Assembly	$276.41	$15.38
1	Concrete ring	$250.00	$13.91
1	Track & encoder ring	$26.41	$1.47
1	Heliostat Structure	$215.91	$12.01
1	Leg Assembly	$41.38	$2.30
1	Leg Assembly Mirror	$41.38	$2.30
1	Elevation Actuator Mounts	$3.06	$0.17
1	Gear Drive Wheel Assembly	$20.83	$1.16
1	Wye	$50.61	$2.82
1	Tension rod assemblies	$14.29	$0.80
	Fasteners	$43.15	$2.40
1	Heliostat Facet Assembly	$828.70	$46.10
1	Facet Frame Assembly	$144.24	$8.02
4	Reflective facets, 1406 mm x 3216 mm	$636.94	$35.43
	Fasteners	$47.52	$2.64
1	Controller	$110.34	6.14
1	Level I and Level II controllers	$41.12	$2.29
1	Trinamic control box (Level III)	$69.22	$3.85
1	Power and energy storage	$111.18	$6.18
1	12 V, 50 W PV Panel	$52.50	$2.92
1	Battery	$49.00	$2.73
1	Wiring	$6.18	$0.34
2	Connectors	$3.50	$0.19
1	Drives	$266.50	$14.83
1	Elevation Drive	$155.57	$8.65
1	Azimuth drive	$110.93	$6.17



Heliostat line item cost	$/heliostat	$/m^2	Basis
Materials & components	$1,809	$100.64	Vendor quotes and representative steel costs
Shipping components to site within U.S.	$27	$1.52	Shipping cost study by ARC
Assembly building and tools	$25	$1.41	ARC manufacturing study for ROP
Field installation equipment rental	$114	$6.36	ARC manufacturing study for ROP
Assembly, installation, and check-out labor	$80	$4.44	ARC manufacturing study for ROP 2.66 man-hr @ 30$/hr, 0.15 man-hr/m^2
Total installed heliostat	**$2,056**	**$114**	

Figure 16 ROP commercial cost breakdown, 60,000 units, Nevada installation

3.8 Conclusions

Table 3 evaluates each task goal according to desired DOE task metrics. In all cases, except one (Lifetime), project goals were met. Development work continues on the drives, control, and PV panel and battery to bring this heliostat to commercialization.

Table 3 - Heliostat task evaluation

Task description	Evaluation metric	Achieved (Y/N)	Basis	If not achieved, pending solution
Beam error under 5 m/s winds	≤ 3 mrad	Y	Convolved error of all sub-components, FEA deflection, tracking results, ARC structural study	-
Beam error under windy conditions (12 m/s)	≤ 4 mrad	Y	Convolved error of all sub-components, FEA deflection, tracking results	-
Wind speed at which to go to stow	≥ 15.6 m/s	Y	FEA, drive testing	-
Wind speed at which heliostat must survive in any orientation	≥ 22.4 m/s	Y	FEA, ARC structural study, survival at SolarTac	-
Wind speed heliostat must survive in stow orientation	≥ 40 m/s	Y	FEA, ARC structural study, survival at SolarTac	-
Lifetime	≥ 30 years	N	Reduction of drive accuracy year 20, intermittent drive & control failures, excessive wheel wear	Continued development
Cost	≤ 120 $/m^2	Y	Vendor quotes and ARC manufacturing study	-