Jet Propulsion Laboratory
California Institute of Technology

Low-cost Lightweight Thin Film Based Solar Concentrators

ASME 2016 Power and Energy Conference

June 26 – June 30, 2016

Gani B. Ganapathi, PI (Jet Propulsion Laboratory/Caltech)
Art Palisoc, Co-I (L'Garde)
Bill Nesmith (Jet Propulsion Laboratory/Caltech)
Andrew Kindler (Jet Propulsion Laboratory/Caltech)
Armin Buchroithner (Graz Institute of Technology, Austria)
Sai Nataraj (Cal State LA)
Gyula Greschik (TentGuild Engineering)
Koorosh Gidanian (KNF Corp.)

Copyright 2016. All rights reserved.

Objectives

Project Objectives

- To reduce the costs to DOE SunShot cost targets of $75/m^2, it was clear that all elements of the concentrator had to be addressed.
- Negotiated with DOE a 3-phase project with several risk reduction and design activities to be performed in the 1st phase. The specific project objectives are:
  - design and development of a mirror module using an inexpensive reflective metalized polymer film bonded onto a light-weight structural rigid foam support,
  - design and development of a low cost nontraditional mirror module support structure,
  - selection of low cost drive components and associated control system,
  - design, integration and testing of a low cost concentrator, and
  - cost analysis of the proposed system to demonstrate $75/m^2 collector system DOE target.
- Project Teaming
  - Led by JPL - Gani Ganapathi PI, Bill Nesmith and Andrew Kindler)
  - Partnership with L'Garde – Art Palisoc, Gyula Greschik and Koorosh Gidanian

Copyright 2016. All rights reserved.

Major Project Phases and Milestones

Phase	Key Milestones and Deliverables
Phase 1 (DESIGN & RISK REDUCTION)	• Material selection & fab processes validated
	• System trades to optimize overall system
Phase 2 (DETAILED DESIGN & FAB)	• Reliability studies for 10 yr life
	• Detailed system trades
Phase 3 (COLLECTOR SYSTEM BUILD & TEST)	• Reliability studies for additional 20 yr
	• Prototype detail design and build
	• Validation testing
	• Commercialization plans

Copyright 2016. All rights reserved.

Design Performance Targets

Metrics from Jesse Gary's report "Heliostat Optical Requirements" used as reference to drive foam dimensions in mirror module

Heliostat Optical Error Budget Summary

Error Type	Allowable RMS Error [mrad]	
	Heliostat Field Average	Heliostat in Worst Combination of Orientation and Wind Speed/Direction
Pointing Errors		
Pedestal Deflections	0.50	1.50
Tracking	1.00	1.00
Residual Offsets	1.00	1.00
Total (in quadrature)	1.50	2.06
Beam Quality Errors		
Focusing/Canting	2.50	2.50
Mirror Module Deflections	1.62	4.86
Temperature Dependence	N/A	N/A
Total (in quadrature)	2.98	5.47
Total Optical Error (in quadrature)	**3.34**	**5.84**

Design driver for studies

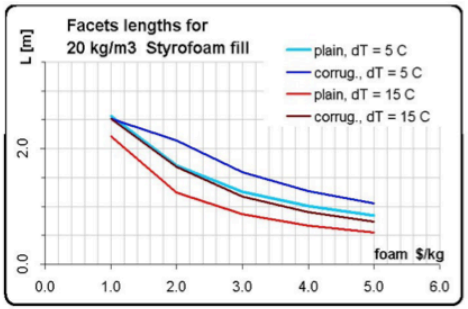
Copyright 2016. All rights reserved.

Facet Design Trades and Outcomes

- Selection of foam material, dimensions driven by performance in windy conditions (4.86 mrad at individual and 1.62 mrad field average in 27 mph)
- Performance metrics and cost drove the design towards a foam sandwich with SS facesheets and ReflectTech mirror film

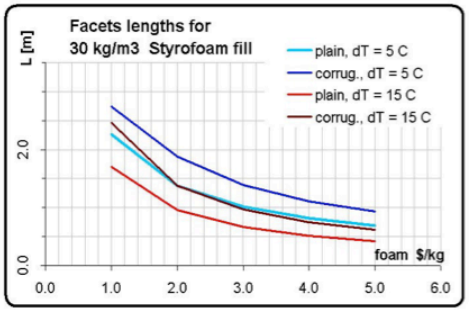
20 kg / m3 Styrofoam: E = 4.76 MPa, G = 3.33 MPa

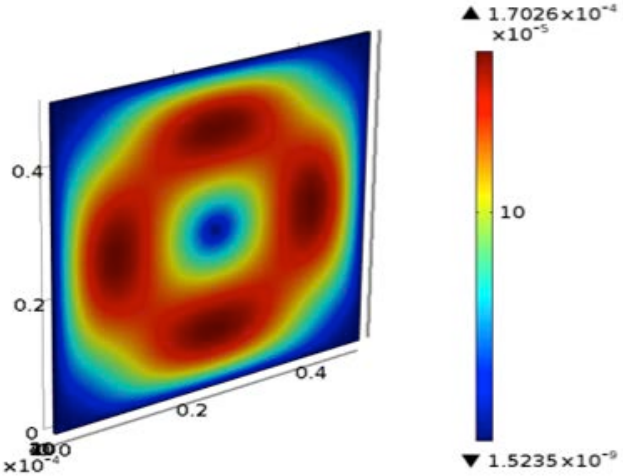
foam fill cost	dT = 5 deg-C between shells: plain facet struct.		corrugated facet struct.		dT = 15 deg-C between shells: plain facet struct.		corrugated facet struct.	
$ / kg	facet length, L [m]	fill thickn. t [mm]	facet length, L [m]	fill thickn. t [mm]	facet length, L [m]	fill thickn. t [mm]	facet length, L [m]	fill thickn. t [mm]
5	0.841	17.8	1.048	30.1	0.549	17.8	0.739	30.1
4	1.003	22.3	1.262	37.7	0.672	22.3	0.906	37.7
3	1.255	29.7	1.596	50.2	0.869	29.7	1.175	50.2
2	1.709	44.5	2.145	75.3	1.239	44.5	1.683	75.3
1	2.569	89.0	2.519	150.7	2.216	89.0	2.519	150.7

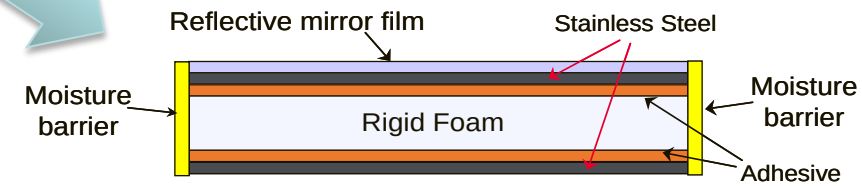


30 kg / m3 Styrofoam: E = 10.0 MPa, G = 7.00 MPa

foam fill cost	dT = 5 deg-C between shells: plain facet struct.		corrugated facet struct.		dT = 15 deg-C between shells: plain facet struct.		corrugated facet struct.	
$ / kg	facet length, L [m]	fill thickn. t [mm]	facet length, L [m]	fill thickn. t [mm]	facet length, L [m]	fill thickn. t [mm]	facet length, L [m]	fill thickn. t [mm]
5	0.691	11.9	0.930	20.1	0.424	11.9	0.615	20.1
4	0.819	14.8	1.108	25.1	0.518	14.8	0.752	25.1
3	1.017	19.8	1.384	33.5	0.669	19.8	0.971	33.5
2	1.375	29.7	1.881	50.2	0.953	29.7	1.381	50.2
1	2.265	59.3	2.742	100.4	1.705	59.3	2.458	100.4

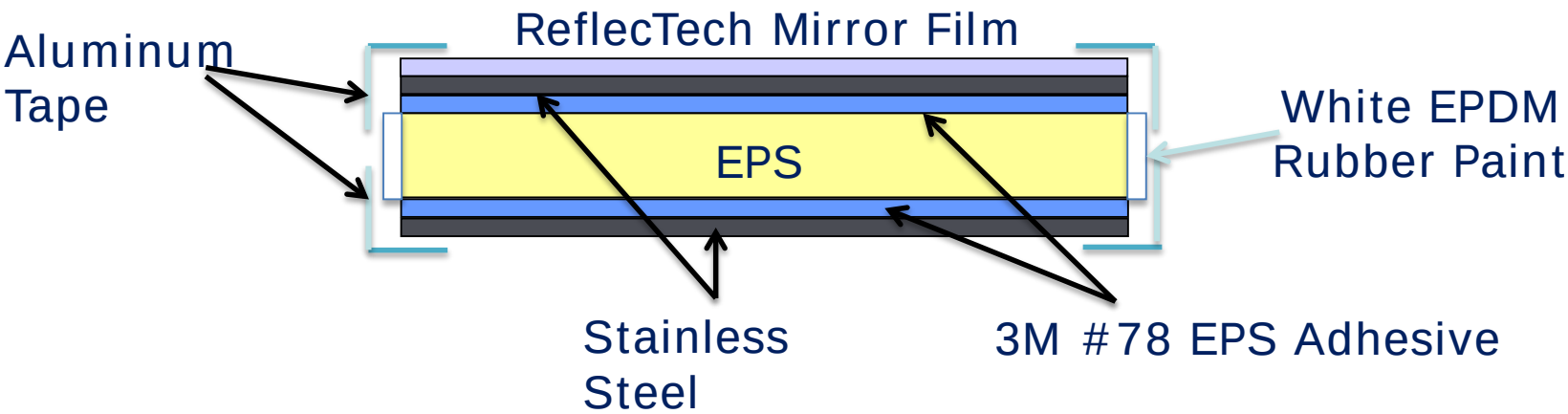






Copyright 2016. All rights reserved.

Mirror Module



- 15 coupons developed for testing
- Test Coupons Identical to Mirror Facet Configuration

Copyright 2016. All rights reserved.

Reliability Testing

Phase II

Thermal Cycling /Humidity Freeze (L•Garde) (per IEC 6218)
Qty:15

Acid Rain/Salt Spray (Exova) – ASTM G85
Qty: 15

Bird Dropping (NTS) – ASTM D6485
Qty: 15

UV Test Equivalent to 10 to 12 years (Solar Light)
Qty: 15

Post-Mortem Tests
(a) Reflectivity vs Wavelength (SOC)
(b) Hardness (Durometer) Test on 3 UV exposed coupons and 3 pristine coupons (Exova OCM)

Phase III

UV TESTED (30 Yr Equivalent)

Post-Mortem Tests
(a) Reflectivity vs Wavelength (SOC)
(b) Hardness (Durometer) Test on
I. 10 UV exposed coupons and
II.12 pristine coupons

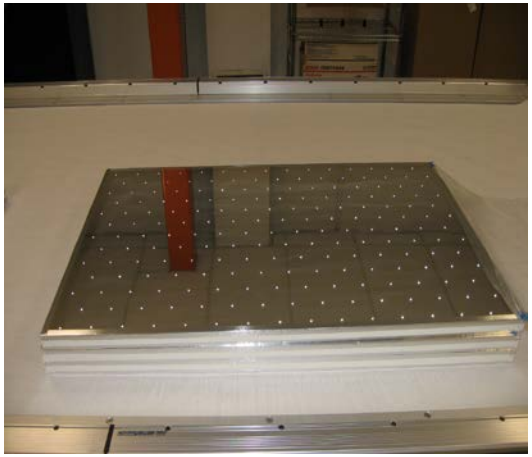
Post-Mortem test results show very little degradation in reflectivity and no degradation of the EPS substrate

Copyright 2016. All rights reserved.

Phase 2 and 3 Mirror Facets

Phase 2 Alpha Concentrators (1m x 1m)

Phase 3 Alpha Concentrators (1m x 0.667m)



- Fabricated 11 mirror facets, and all have been characterized optically with photogrammetry.
  - Average RMS slope error ~ 0.86 mrad
- Optical characterization validated independently at JPL using Reverse Hartmann
  - Average RMS slope error ~ 0.6 mrad

Copyright 2016. All rights reserved.

Design performance targets

Metrics from Jesse Gary's report "Heliostat Optical Requirements" used as reference to drive foam dimensions in mirror module

Heliostat Optical Error Budget Summary

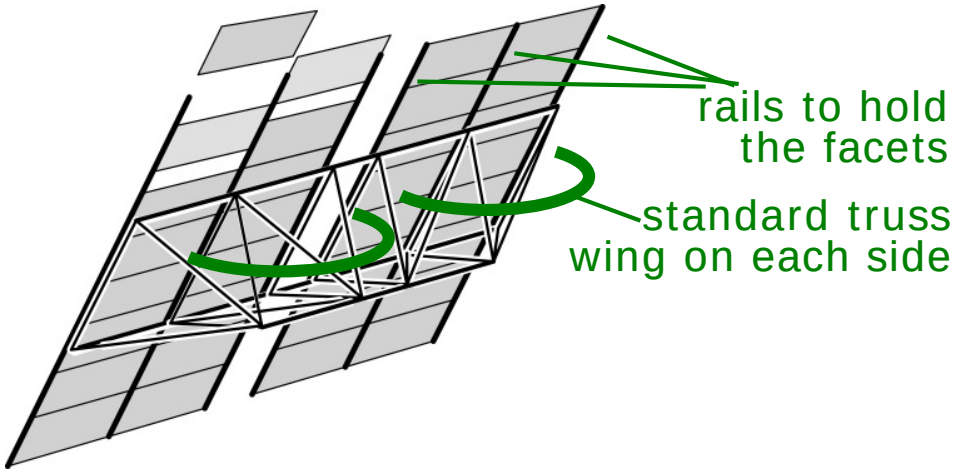
Error Type	Allowable RMS Error [mrad]	
	Heliostat Field Average	Heliostat in Worst Combination of Orientation and Wind Speed/Direction
Pointing Errors		
Pedestal Deflections	0.50	1.50
Tracking	1.00	1.00
Residual Offsets	1.00	1.00
Total (in quadrature)	1.50	2.06
Beam Quality Errors		
Focusing/Canting	2.50	2.50
Mirror Module Deflections	1.62	4.86
Temperature Dependence	N/A	N/A
Total (in quadrature)	2.98	5.47
Total Optical Error (in quadrature)	**3.34**	**5.84**

Design driver for studies

Copyright 2016. All rights reserved.

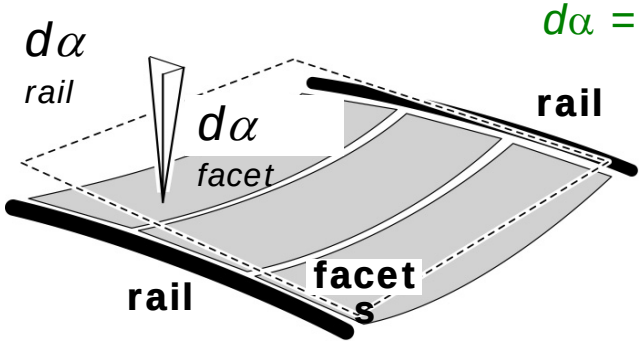
Truss-based design selected

- **Modular structural schematic**
  - ✓ Facets simply supported beam between rail pairs
  - ✓ Simple sandwich construction chosen **from several alternatives**



- **With rationally budgeted error limit**
  - ✓ 4.86 mrad → 1/3 (1.62 mrad) truss + 2/3 (3.24 mrad) facet & rails
  - ✓ 3.24 / √2 = 2.291 mRad for each of facet & rail deformations, because they are orthogonal

$$d\alpha = (d\alpha_{facet}^2 + d\alpha_{rail}^2)^{1/2}$$



$$e_{RMS,d\alpha} = (e_{RMS,d\alpha\ facet}^2 + e_{RMS,d\alpha\ rail}^2)^{1/2}$$

Copyright 2016. All rights reserved.

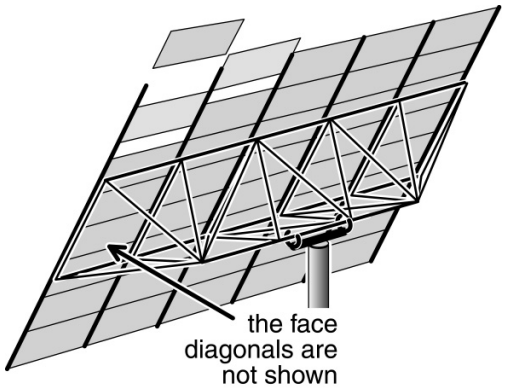
System Studies

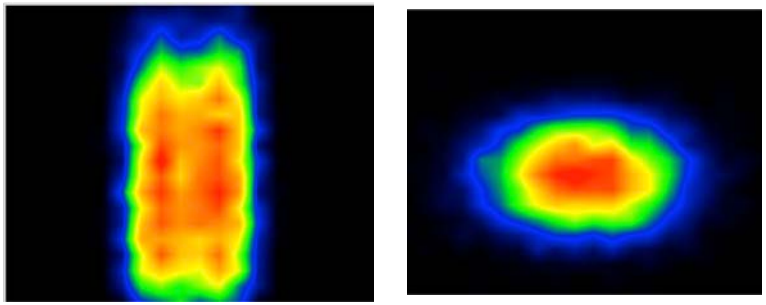
- Goal to optimize system configuration and cost
- Looked at several different system studies
  - Controls – open loop vs closed
  - Actuator types – linear vs slew drives, deep actuator
    - Deep structure actuators - Due to inherent implementation challenges and no cost advantages accruing, the deep structure option was abandoned from further consideration.
  - Standalone heliostats
    - Independently controlled
    - Independently powered
      - – cost benefits convincing enough to warrant development (next slide)
  - Thermal analyses – studies done to understand and reduce temperature gradients across foam structure
    - Found painting backside white was sufficient to keep gradients within 5-8 °C

Copyright 2016. All rights reserved.

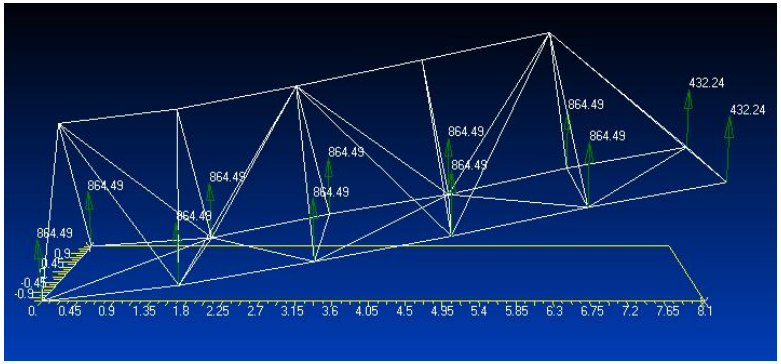
Structure Trades and Outcome

- 3 designs traded with 2 materials – Al 6061 and Steel
  - "Flagpole", small heliostat "islands", optimized truss-based
  - Optimized truss best for cost and mass





Soltrace images at receiver
25m and 500m



Slope error < 1.62 rms
Mass < 80 kg
Cost ~ $4/m^2

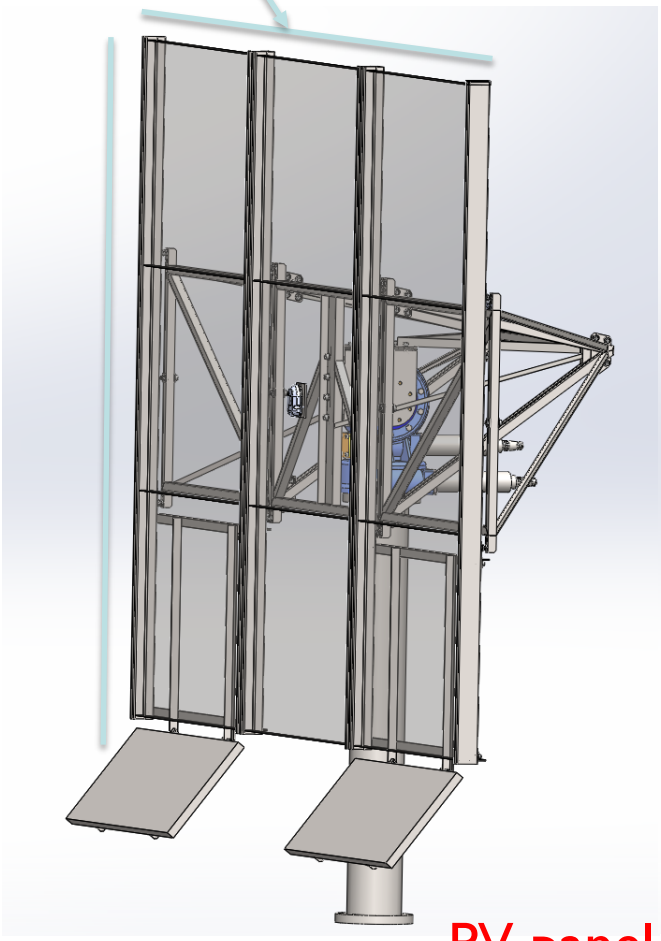
Copyright 2016. All rights reserved.

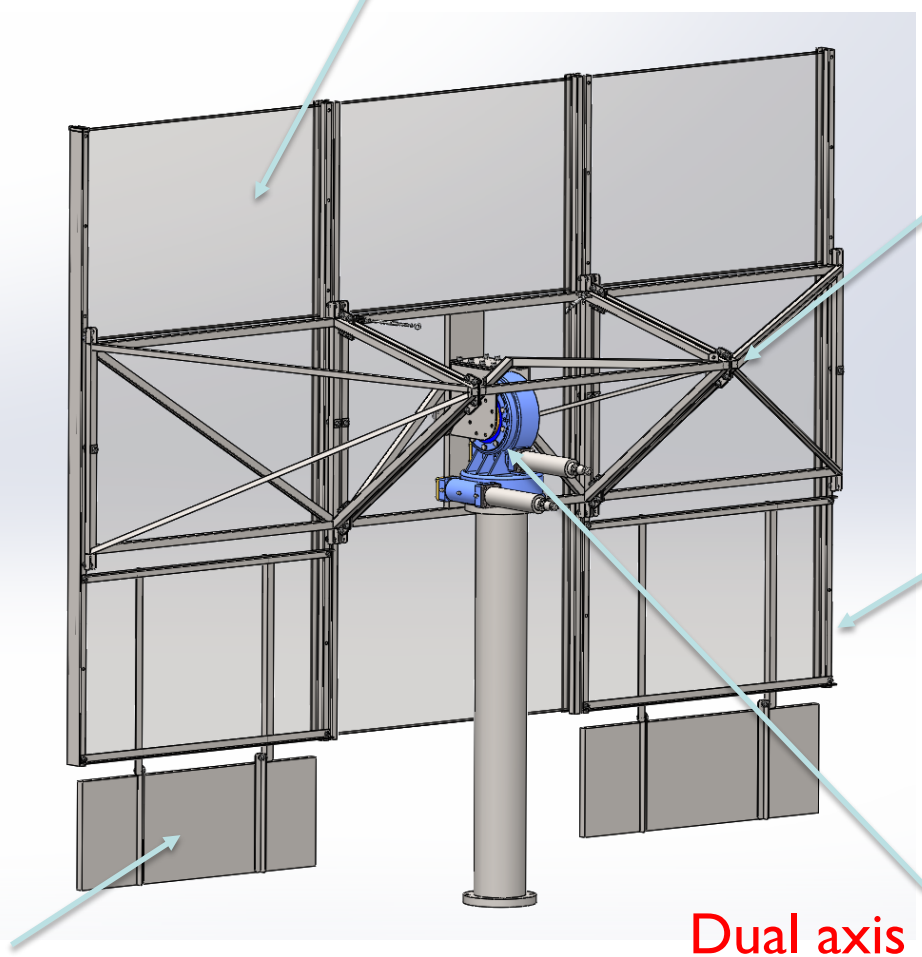
CAD and important design features

Envelope: 3x2 m

9 facets each 0.667x1m and 1.25" thick

3 truss elements





C-rails

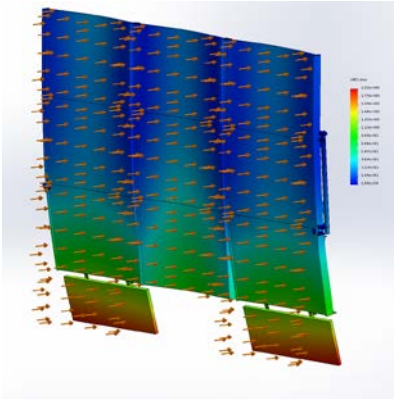
PV panel

Dual axis slew drive

Copyright 2016. All rights reserved.

Finite Element Analysis of Prototype

- Model was cleaned up and simplified for meshing
- FEA in *SOLIDWORKS*, *ANSYS* and *COMSOL Multiphysics*
  - Simplifications: drive = rigid body connection



- Load cases investigated:
  1) Deflection and stress under
  2) 35mph winds at 0, 45 and 90°elevation angle
  3) Dynamic response and eigenfrequency
  4) Impact of PV panel on deflection
  5) Stress during stowed condition (85 mph)

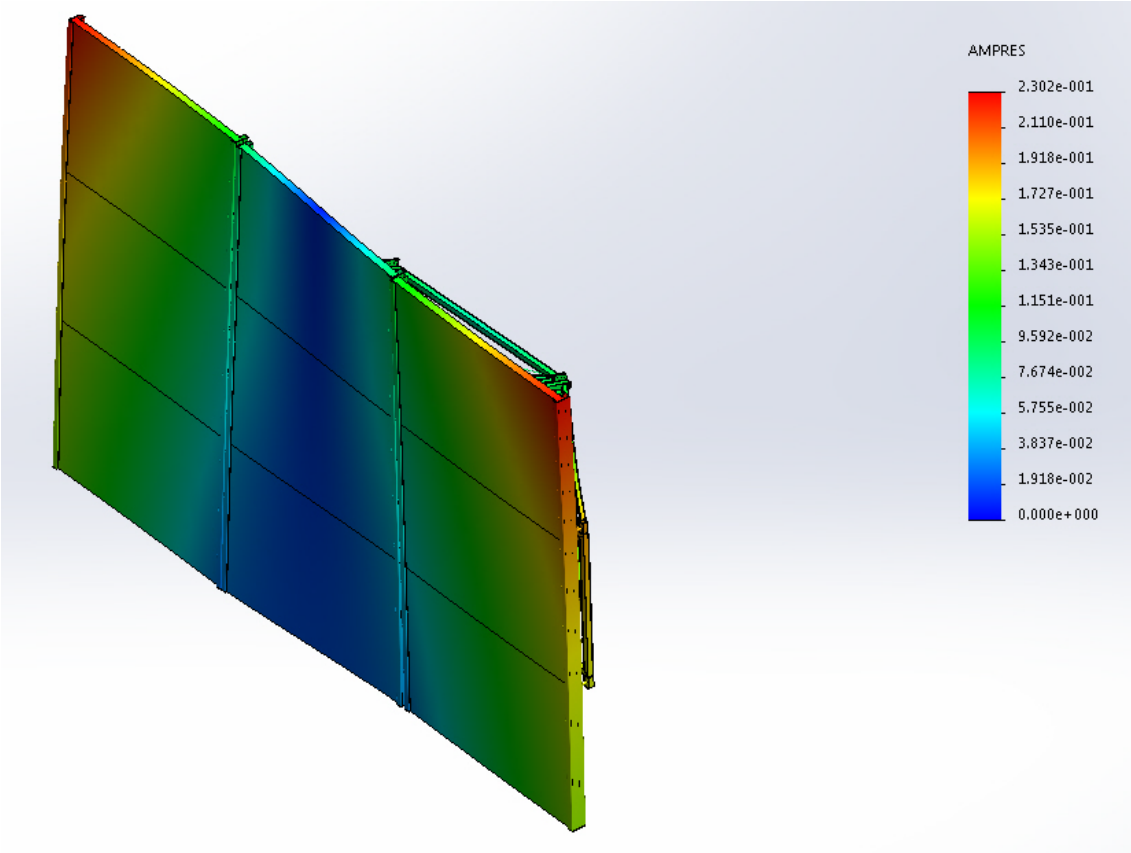
Copyright 2016. All rights reserved.

FEA Results - Dynamic response and eigenfrequency

Vibrations triggered by wind or vortex shedding are among the most severe error sources for heliostats

- →Resonance frequency of the structure needs to be investigated

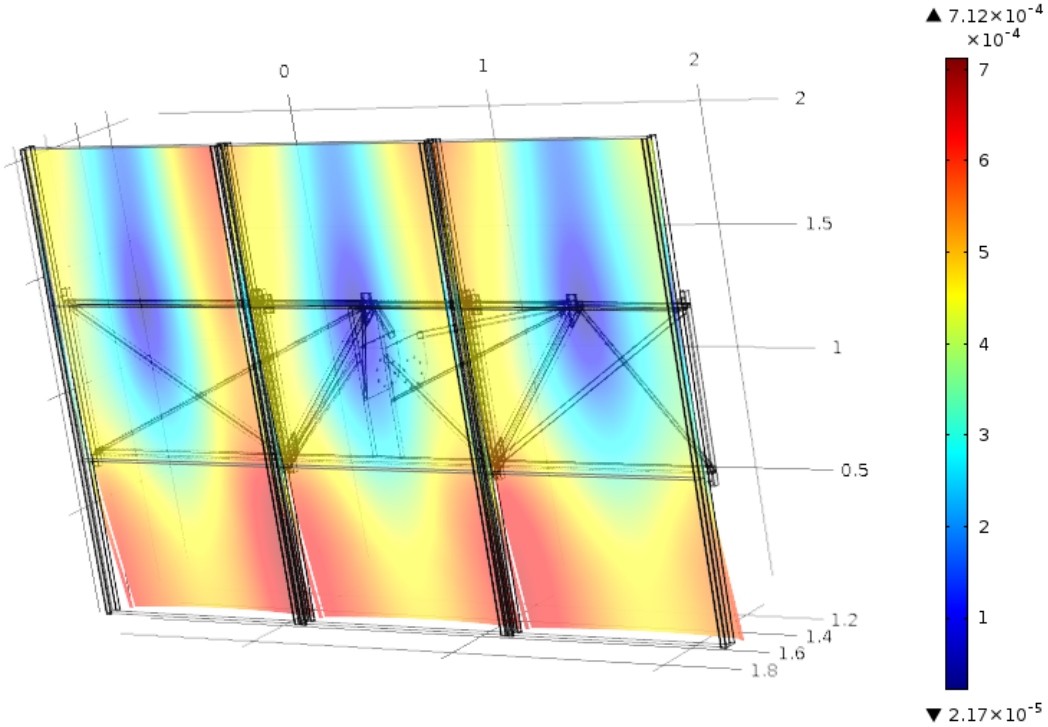
- First 5 eigenmodes were found to be in the 17 to 20 Hz range
- Simulated frequency was higher than real values because of simplifications
- Model was validated with measurement data



Copyright 2016. All rights reserved.

FEA Results – Other findings

- PV panels at bottom increase deflection from 0.8mm to 1.5mm
- The maximum slope error was 0.71 mrad (COMSOL) near the attachment points for the facets at the bottom. Averaging across the entire face of the heliostat, the **average slope error was calculated to be 0.4 mrad.**



Copyright 2016. All rights reserved.

Fabrication of Mechanical System (Prototype)

Mirror facets: L·GARDE SMART SPACE TECHNOLOGY

C-rails: A&M Metal Forming Welding, Inc. Since 1952

Truss elements: ADVANCED TECHNOLOGY COMPANY

Fastening & Joining: McMASTER-CARR

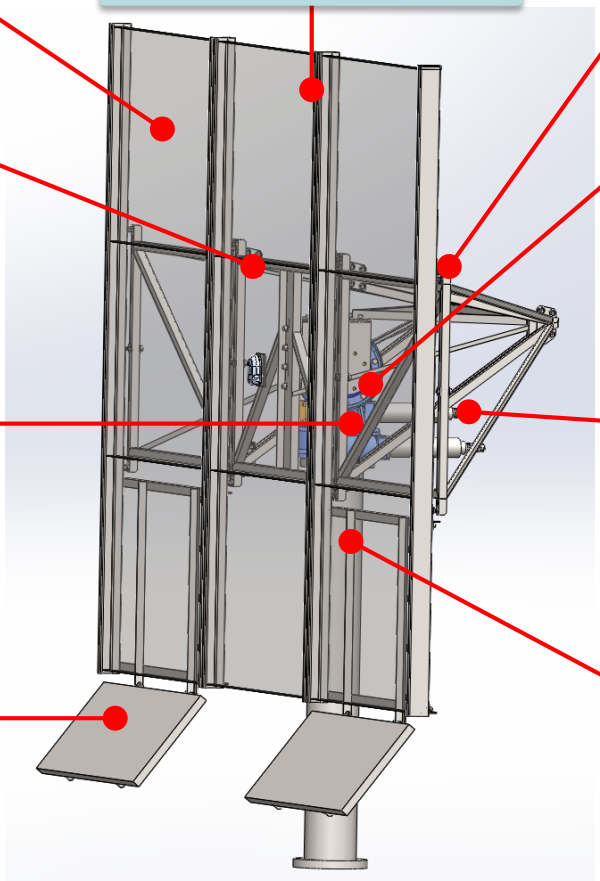
Dual axis drive: KMI Kinematics Manufacturing — Process Solutions through Excellence in Innovation

Sensors: OMRON AUTOMATION & SAFETY

Electrical: MOUSER ELECTRONICS

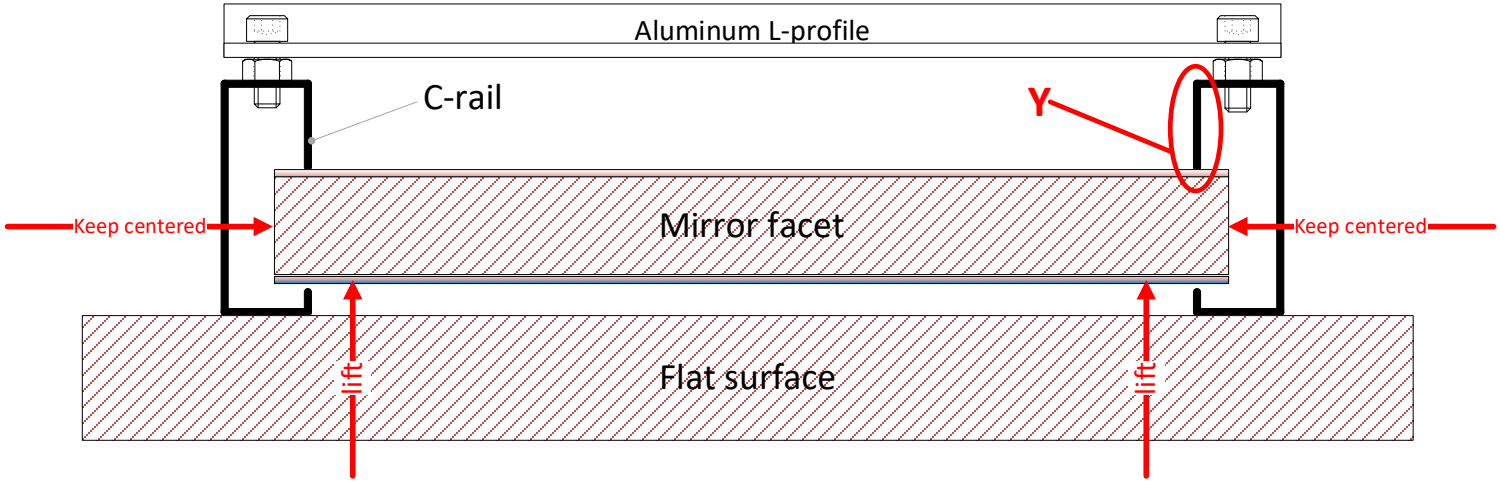
PV Panels: IRON EDISON

Control hardware: ATMEL



Copyright 2016. All rights reserved.

Prototype Assembly – mirror module assembly



- ✓ C-rails were clamped on optical table
- ✓ Aluminum gage was used to space rails
- ✓ Glue was applied

Copyright 2016. All rights reserved.

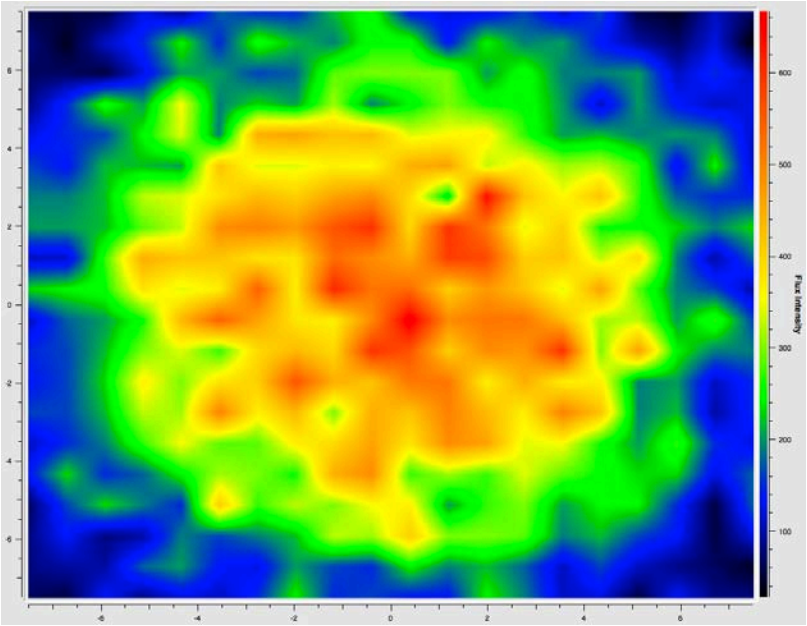
Prototype Assembly – integration of PV panels

- ✓ Aluminum struts for PV mounts were manufactured
- ✓ PV panels were mounted on c-rails
  - Angle is easy to adjust
  - Slight compliance noted

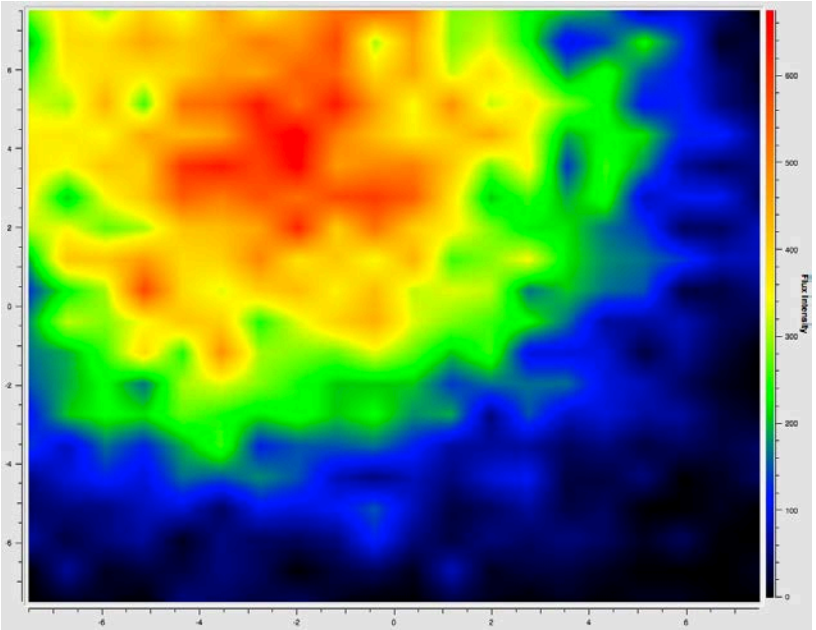
Copyright 2016. All rights reserved.

SolTrace Optical Model

- Control algorithm developed with error sources
  - Pedestal tilt, axis bias angle, non-orthogonality, canting, gravity sag
- Real pointing vector input into SolTrace
- Assumptions:
  - Square 100 m^2 heliostat and square 225 m^2 receiver
  - Heliostat with 0.94 reflectivity (Reflect-Tec)
  - Heliostat slope error of 1.5 mrad, specularity error of 0.2 mrad



Ideal Pointing Flux Density Map
Total Integrated Flux = 59569 W



Real Pointing Flux Density Map
Total Integrated Flux = 48527 W

Copyright 2016. All rights reserved.

Error Model Flowchart

- The error model provided by Malan[1] has been expanded. The new mathematical model describes the following error sources:
  - Pedestal tilt error
  - Axis bias angle error
  - Non-orthogonality error
  - Translation error
  - Canting error (Stone[2])
  - Gravity sag error (Stone[2])

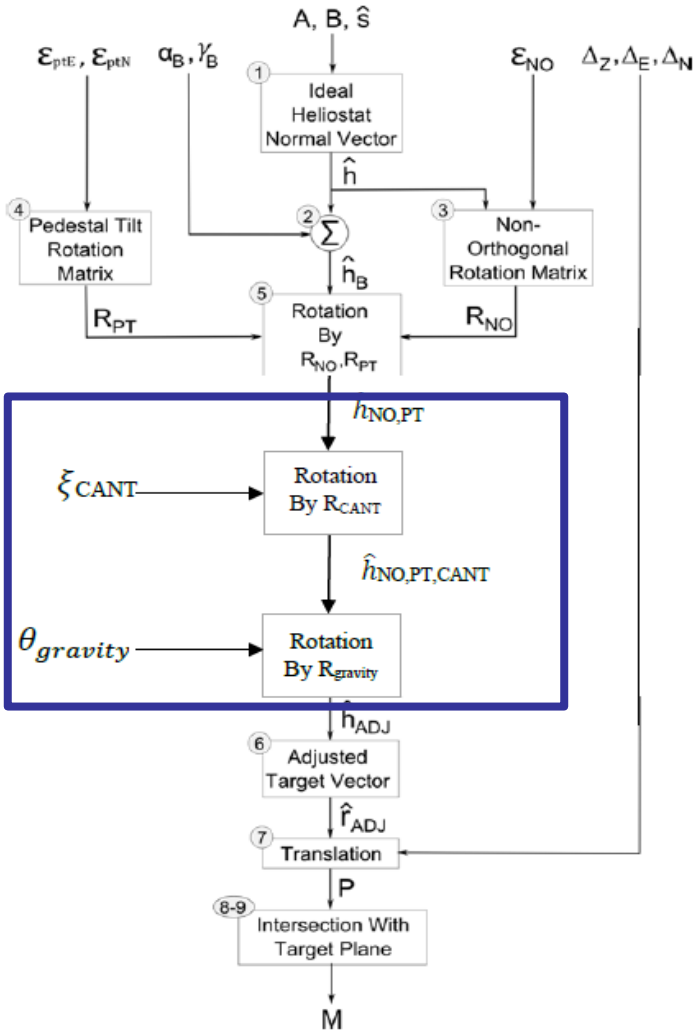
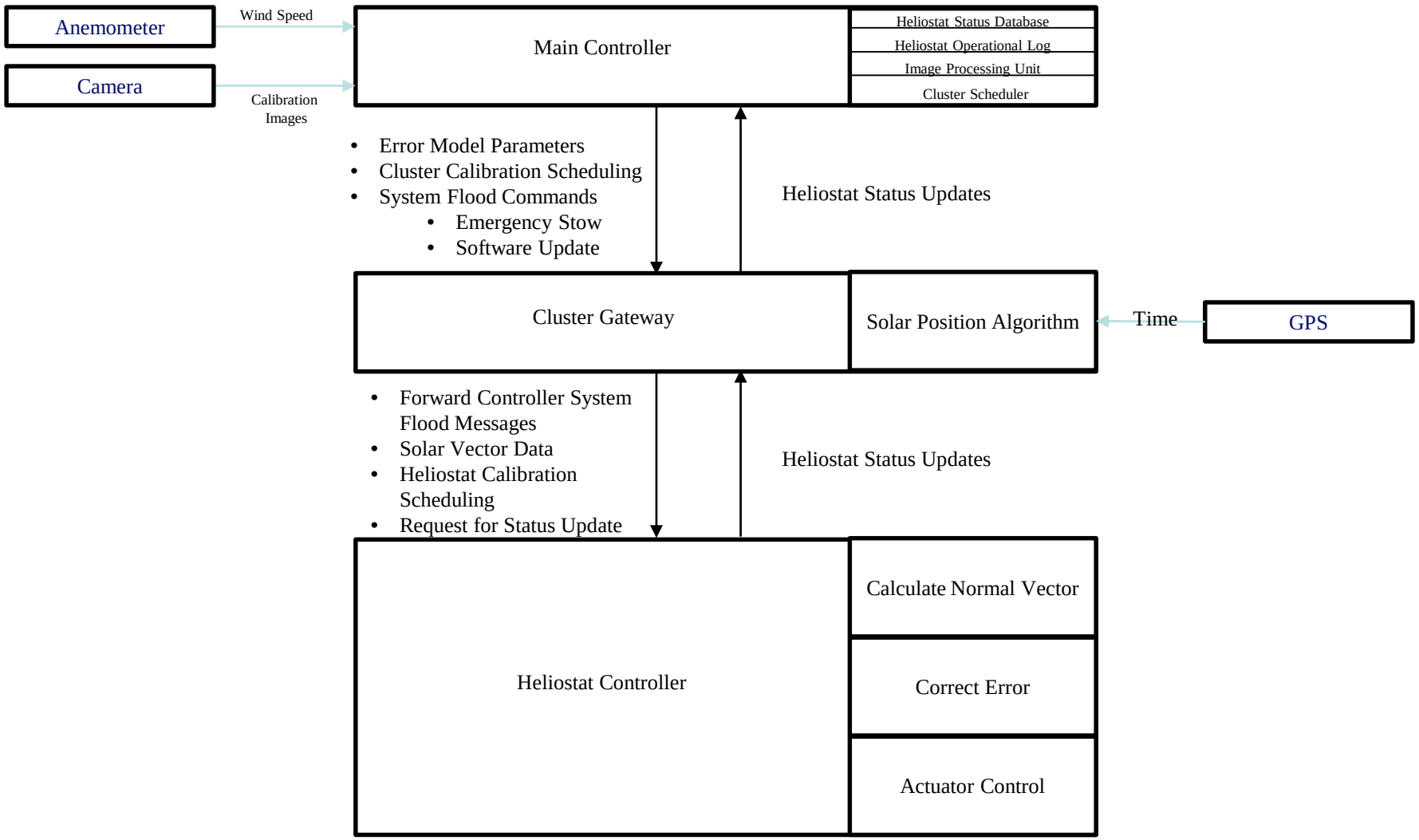


Figure 1: Revised Error Model Flowchart

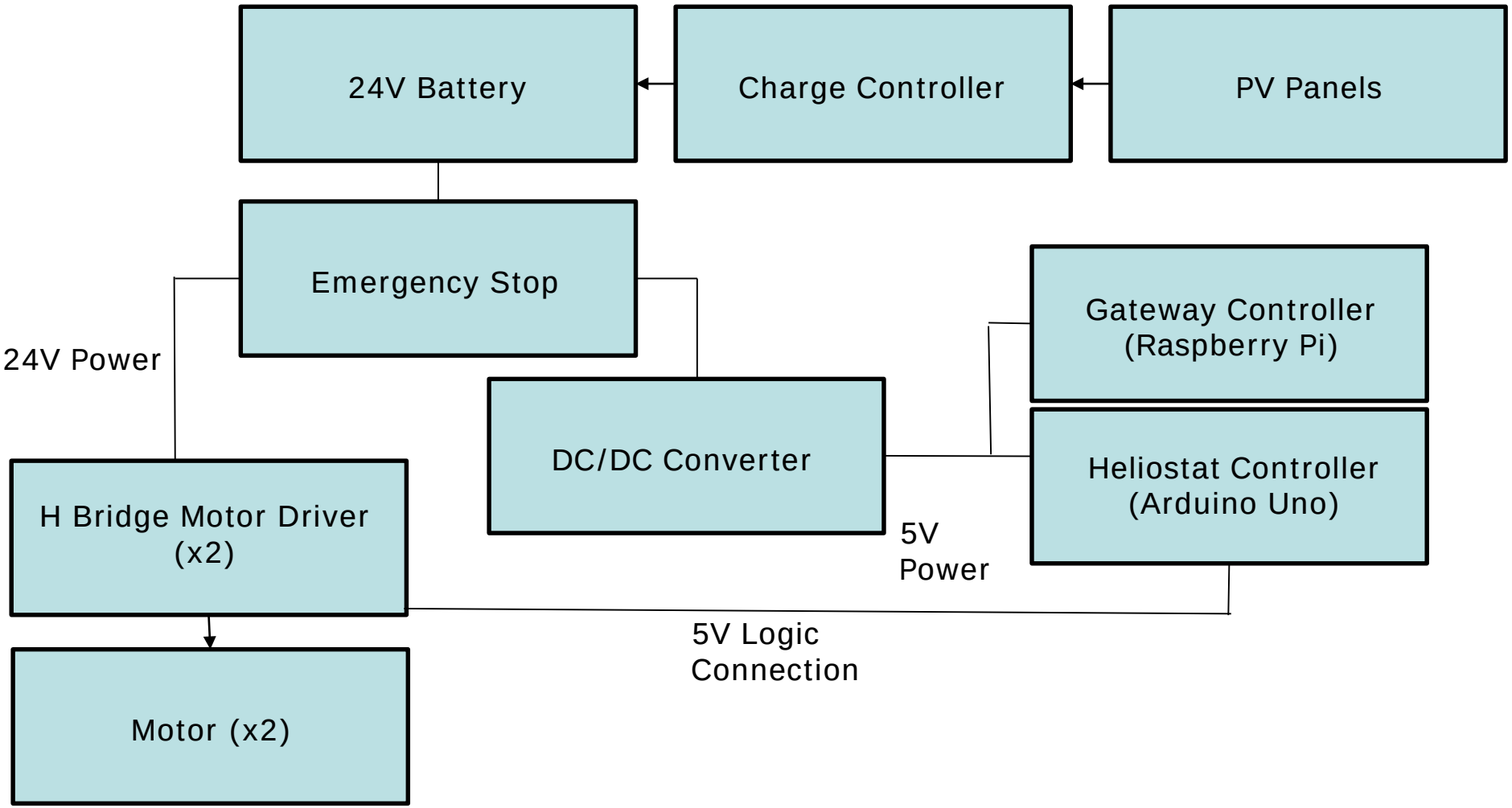
Copyright 2016. All rights reserved.

Control System Architecture



Copyright 2016. All rights reserved.

Integration of Power and Control Systems



Copyright 2016. All rights reserved.

Validation testing

- The original validation test was quite ambitious in scope, but had to be re-scoped to address the following key goals:
  - Validate structural model through point loading
  - Demonstrate independent tracking
  - Demonstrate self-powered tracking with adequate power and energy margins

Copyright 2016. All rights reserved.

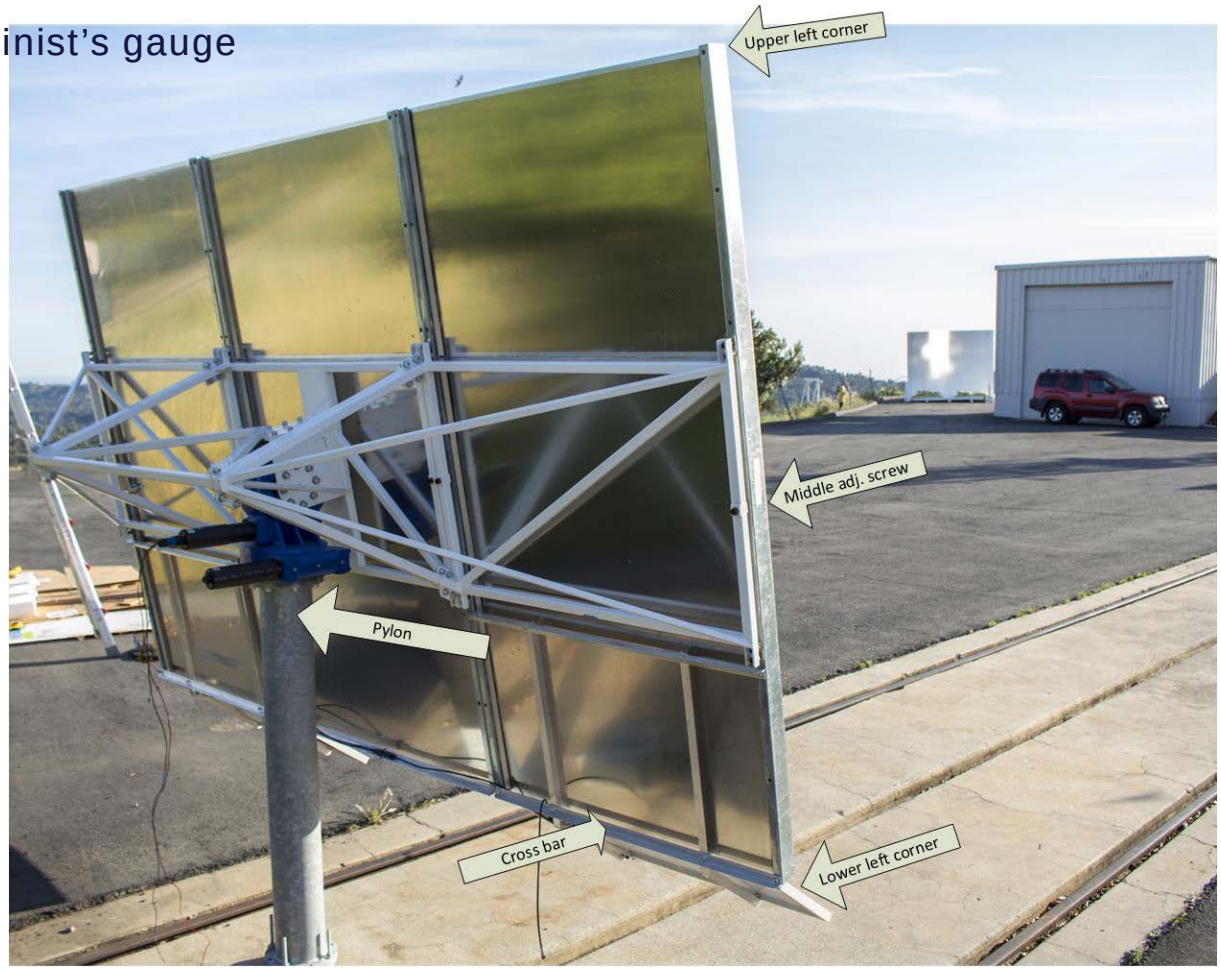
Site Selection

Copyright 2016. All rights reserved.

Support structure deflection test

Time and budgetary constraints required a different “quick and easy” solution

- point load applied by spring scale
- deflection measured with machinist’s gauge

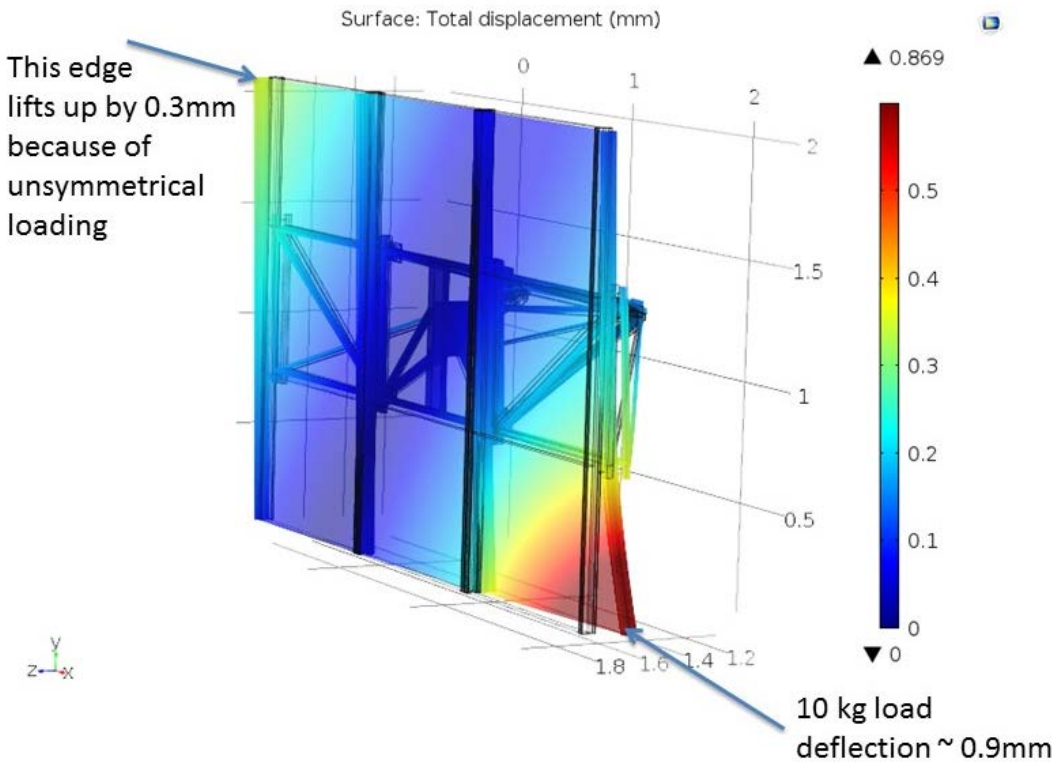


Copyright 2016. All rights reserved.

Support structure deflection test – comparison with FEA

- **Measurement:** force of 10 kg (or 98 N) deflects the c-rail 0.11 inches (2.8 mm)
- **Simulation:** *COMSOL* (~0.9 mm) *Solidworks* (~1.2 mm), *ANSYS* (~1.65 mm)

Point load on lower corner



Deviation due to:

- Rigid connection in FEA
- Drive and pylon neglected in FEA
- Backlash of worm gears (~1.65 mm)

Copyright 2016. All rights reserved.

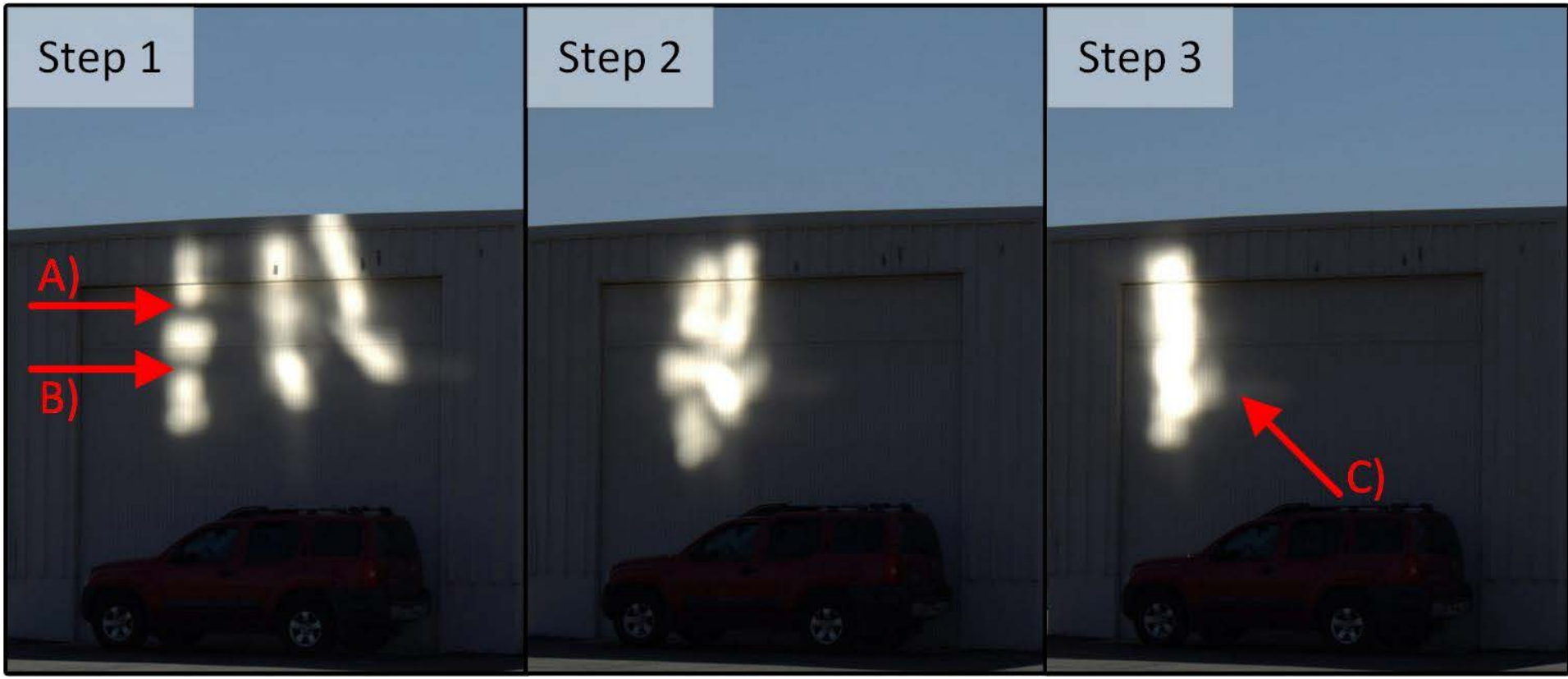
Heliostat Image Adjustment

- Immediately after the heliostat prototype was assembled an image was projected to a wall about 50m (~150 feet) away.
- Since none of the canting and focusing options had been tested, the initial image was rather spread out.

Formerly discarded facet re-used

Copyright 2016. All rights reserved.

Heliostat Image Adjustment



- The range of the adjustment screws was sufficient
- Aluminum tape does not reflect the light as well and results in a dark area between The bright spots of each facet (indicated as **A)** and **B)**
- Previously discarded “wavy” facets cause spill of radiation **C)**

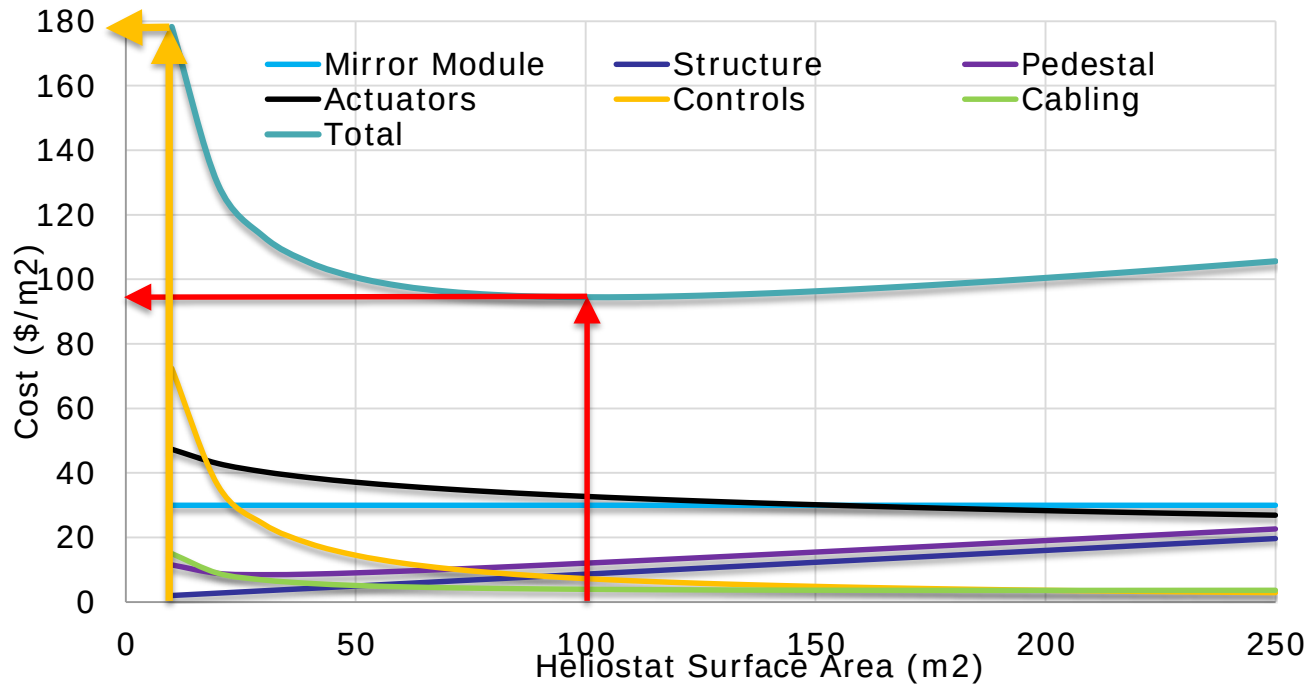
Copyright 2016. All rights reserved.

Large scale (~100m²) design at high production volume

Some components show a non-linear "$/m²-characteristic" when scaled

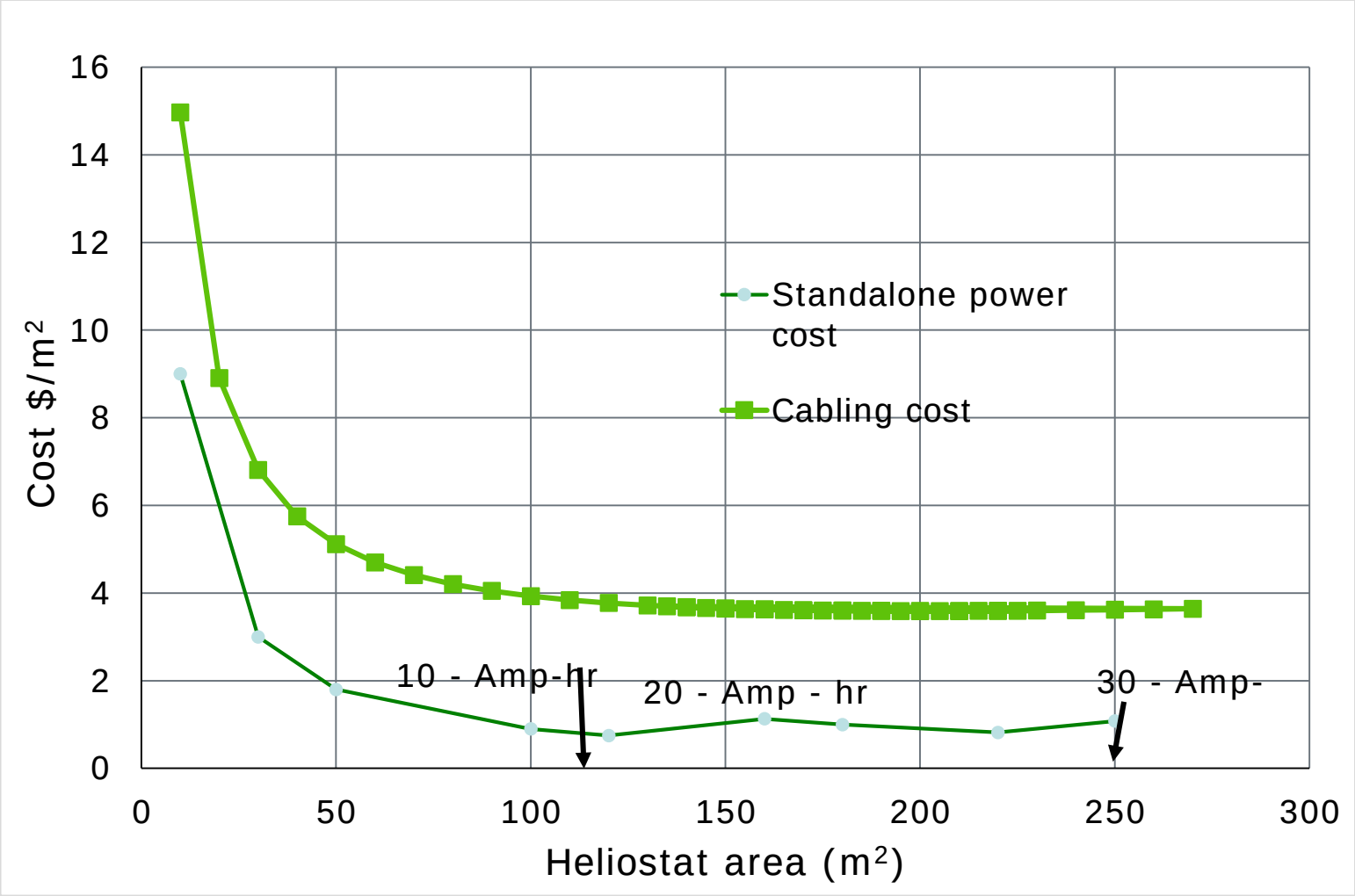
- Small heliostat slew drive: $ 500 for 6m² → $83/m²
- Large heliostat slew drive: $ 2500 for 100m² → $25/m²

Factor ~1.85



Copyright 2016. All rights reserved.

System Studies – Standalone power vs cabling cost



Copyright 2016. All rights reserved.

Large scale (~100m²) design at high production volume

Cost Element	L'Garde Estimate (100 m2)	JPL Estimate (6 m2)	JPL Estimate (100 m2)	Comments
Labor	$18.10	$24.00	$13.00	JPL cost did not include shipping to jobsite. Labor scaled
Mirrors	$38.19	$38.19	$38.19	L'Garde estimated the cost of the mirrors
Tubing/Truss	$8.60	$1.70	$8.60	Material cost + scale for torque (Phase 1)
C-rails	$4.60	$4.60	$4.60	JPL estimate
Pedestal or Pylon	$12.00	$8.00	$12.00	Material cost + scale for torque (Phase 1)
Foundation	$2.82	$2.82	$2.82	L'Garde estimate
PV modules	$0.50	$3.50	$0.50	JPL estimate based on Ph2 scaling for power
Battery + charger	$0.65	$6.50	$0.65	JPL estimate. Power scaling based on Ph2 battery+PV trades
Controller	$0.75	$7.50	$0.75	JPL estimate. Ph1 scale used for 6m2 → 100m2
Slew Drive	$14.71	$60.00	$25.00	L'Garde estimate based on ATS report. JPL estimate based on vendor data for dual-axis slew drive (KMI). Could be lowered by linear actuators
SubTotal	**$100.92**	**$156.81**	**$106.11**	
Profit (10%)	$10.09	$15.68	$10.61	10% profit
Grand Total	**$111.01**	**$172.49**	**$116.72**	

Costs can be reduced further by use of float glass

The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

Copyright 2016. All rights reserved.

Commercialization

- Engaged large CSP vendors – early interest shown in mirror modules
- Patents filed
- L'Garde investing IR&D funds

Copyright 2016. All rights reserved.

Summary

- JPL and L'Garde have demonstrated through a well-thought out and rigorously implemented 3-phase project that it is feasible to develop low-cost concentrators which are:
  - Modular in design
  - Low-cost and lightweight lending to easy installation in the field
  - Capable of being easily canted to focus image
  - Standalone with self-contained power system and controller
- Commercialization efforts are on-going and we believe there is a market for such a design

Copyright 2016. All rights reserved.

Acknowledgements

Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The effort was supported by DOE's SunShot CSP R&D Funding Opportunity DE-FOA-0000595 and cost share from L'Garde, Inc.

Copyright 2016. All rights reserved.