POLYMERIC MIRROR FILMS: DURABILITY IMPROVEMENT AND IMPLEMENTATION IN NEW COLLECTOR DESIGNS

SunShot CSP Program Review 2013

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Awardee: 3M

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Outline

- Background and Objectives
- Technical Approach and Results
- Summary and Key Lessons

- CSP Cost Reduction and Solar Collectors
- Film based Solar Collectors
- Conclusions

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Project Objectives and Outcomes

Objectives

- Develop novel optical coatings for silvered polymeric mirrors with PMMA front surfaces
- Contribute to cost reduction in CSP solar field
- Demonstrate manufacturing processes for these optical coatings and incorporate onto mirrors
- Validate the impact of these novel optical coatings in field trials (Abengoa, Gossamer Space Frames)

Expected Outcomes

- Decrease the rate of loss of specular reflectance by 50%
- Decrease the rate of irreversible soiling by 50%
- Reduced frequency of cleaning and O&M costs
- Expand mechanical cleaning options
- Positive impact on LCOE by enabling reflective film based collector designs

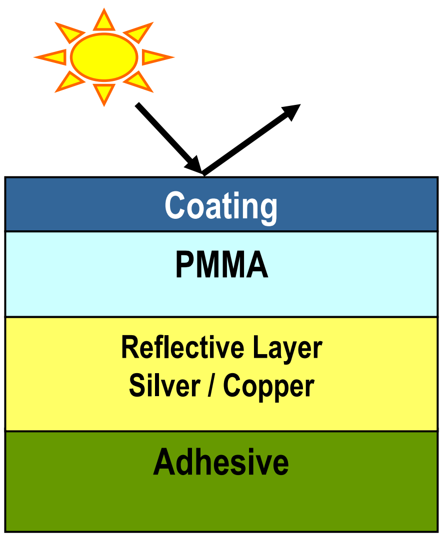
3M Silvered Polymeric Mirrors: Substrates for Coating Development

Description

- Broadband solar reflector based on metalized polymer film
- Silver as reflective layer

Key Features

- Film-based reflector enables design flexibility & optimization
- High reflectivity and specularity
- Break resistant
- Low weight
- Scalable manufacturing



Property	3M Solar Mirror Film 1100
Solar Weighted Hemispherical Reflectance (G173)	94.5%
Specular Reflectance at 25 mradian acceptance angle	95.5%

Source: S. Meyen et. al, Standardization of Solar Mirror Reflectance Measurements Round Robin Test, SolarPACES 2010

Projects using Solar Mirror Films

Abengoa Solar, El Tosoro Chile
10 MW thermal
Uses 3M SMF 1100 Mirror Film
Commissioned Fall 2012

Photo Courtesy Abengoa Solar

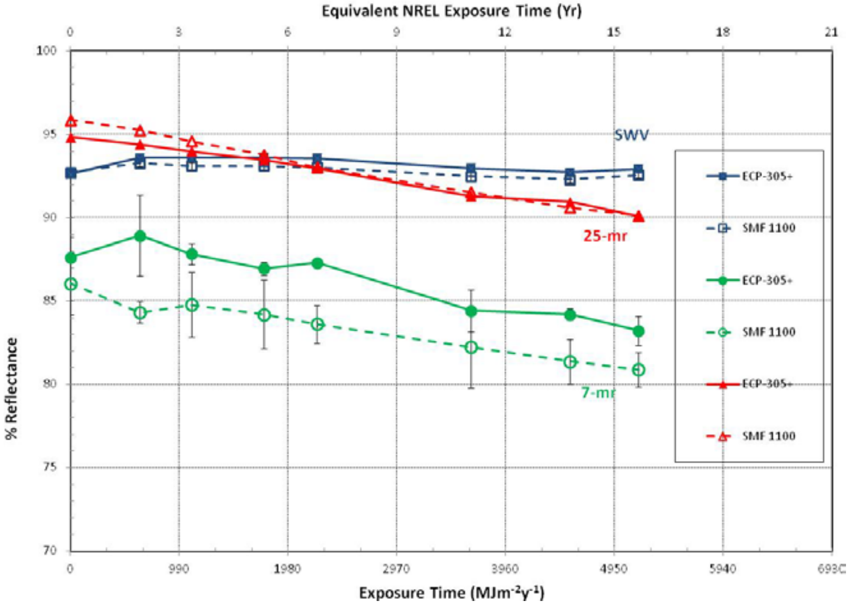
Abengoa Solar, Englewood, CO USA
1.2 MW thermal
Uses 3M SMF 1100 Mirror Film
Commissioned June 2010

Photo Courtesy Abengoa Solar

Mirror Films: Key Durability Concerns

- Resistance to UV degradation
- Abrasion resistance
- Interlayer delamination

Courtesy: C. Kennedy, NREL



Courtesy: C. Kennedy, NREL

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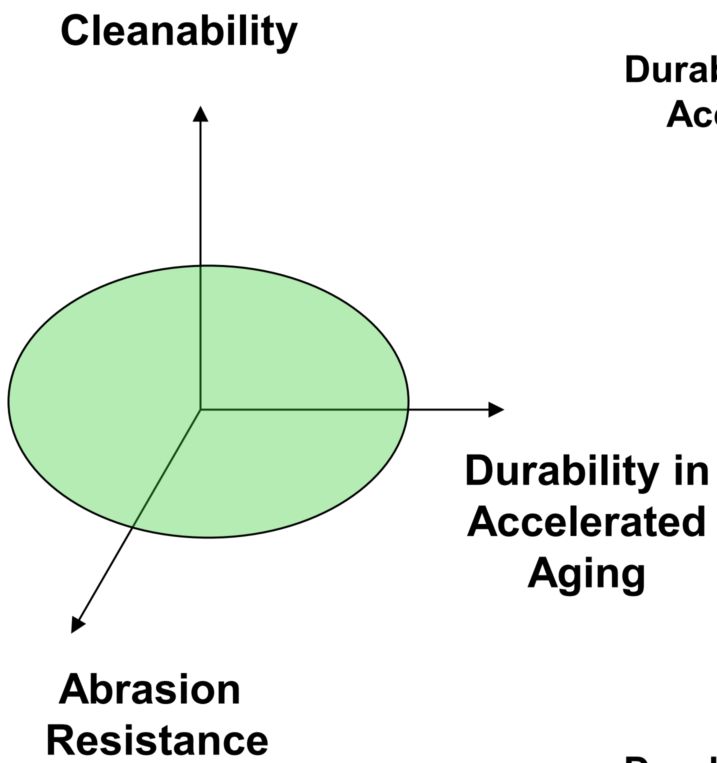
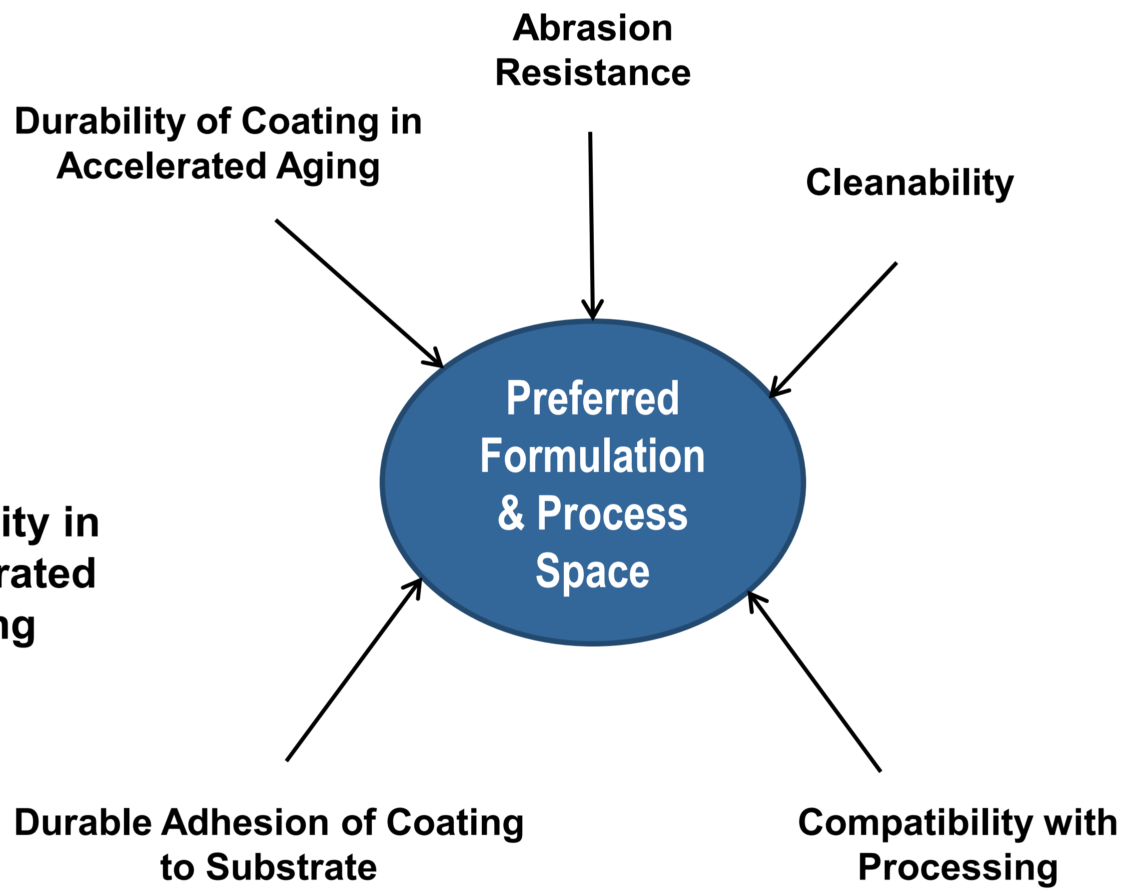
Optimization of Coating Properties





Balancing performance of virgin coatings against durable adhesion and compatibility with processing is critical to durable function

Mirror Durability Considerations

Failure Mode	Root Cause(s)	Impact	Test Methods
Corrosion	Coating failure Edge sealing failure	Mirror graying Loss of reflectivity	Damp heat Outdoor exposure
Abrasion	Installation Windborne sand Low surface hardness	Loss of specularity	Taber abrasion Falling sand
Radiative degradation	Poor UV protection	Hazing Loss of reflectivity	Xenon arc UV exposure Outdoor exposure
Delamination	Low interlayer adhesion Liquid moisture with edge seal failure	Loss in specularity	Water immersion Salt water immersion Outdoor exposure
Yellowing	Chemical interactions	Loss of reflectivity	UV exposure Colorimeter Outdoor exposure
Thermal degradation	CTE mismatch Water intrusion	Delamination	Thermal cycling Freeze-thaw

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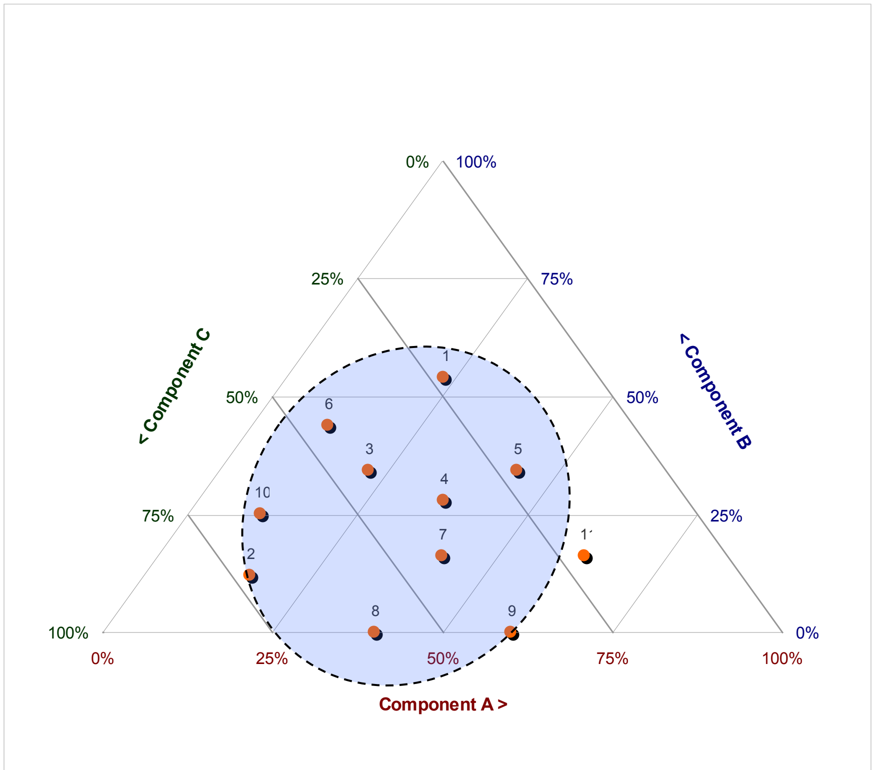
Technical Approach



- Optics
- Adhesion
- Abrasion Resistance
- UV Resistance
- Moisture Resistance
- Thermal Resistance

Technical approach balances chemistry, durability and weathering to create a reliable solution at optimal cost

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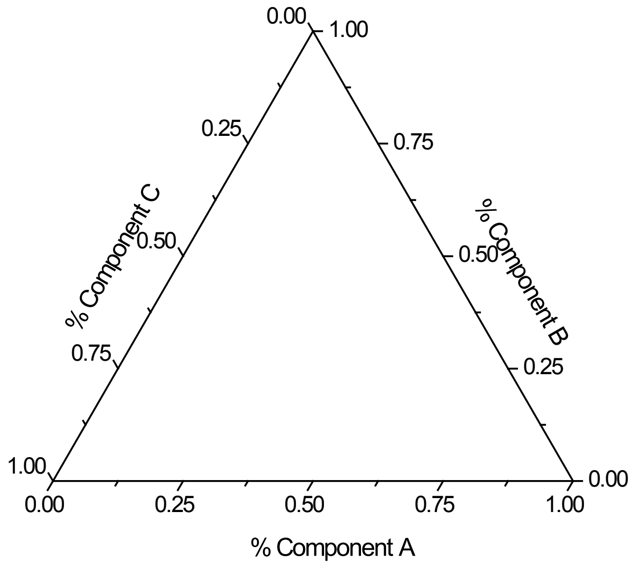
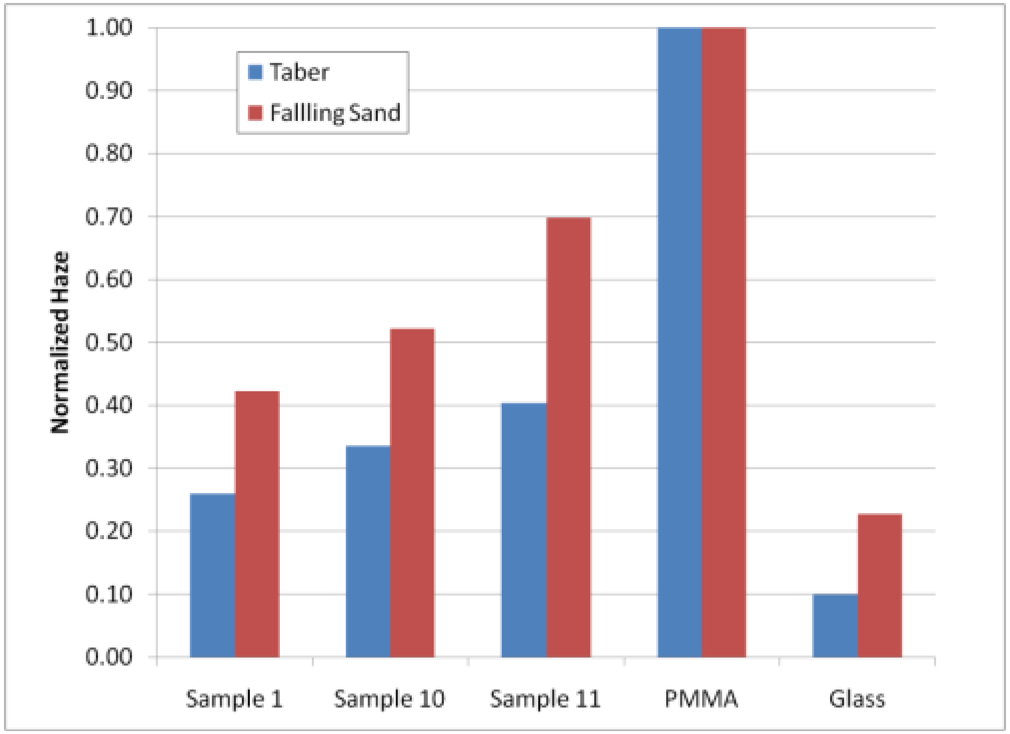
Key Accomplishments:
Durable Coatings with Durable Adhesion





Demonstrated 30-75% improvement in abrasion resistance, retention of performance after >5000 h or accelerated weathering

* 3M Proprietary Exposure Cycle

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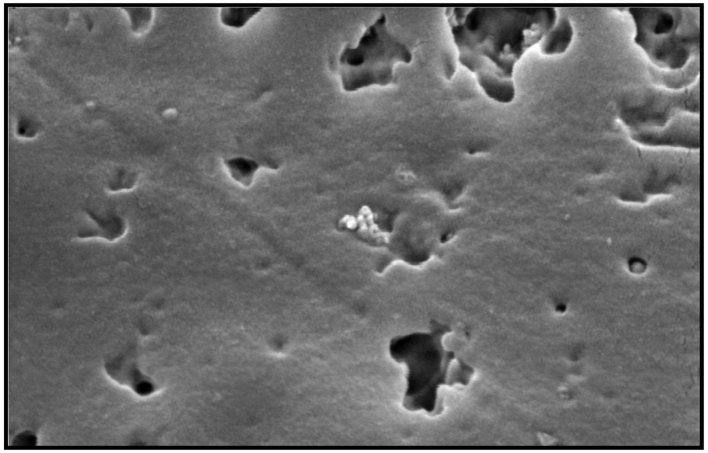
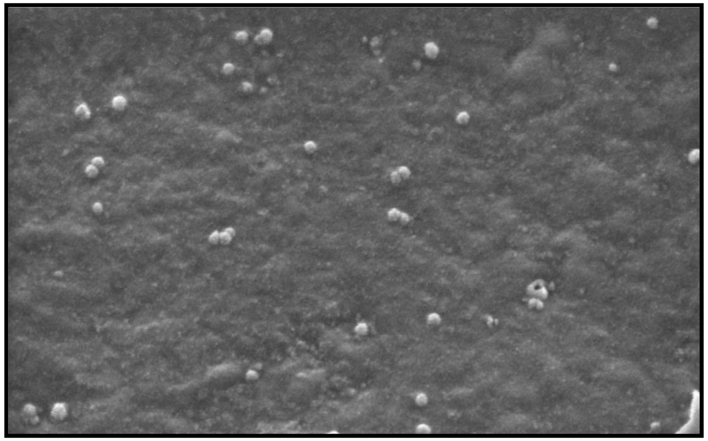
Key Accomplishments:
Durable Coatings with Durable Adhesion

Surfaces of Weathered Samples
4000 h*, 60,000 x Magnification



PMMA

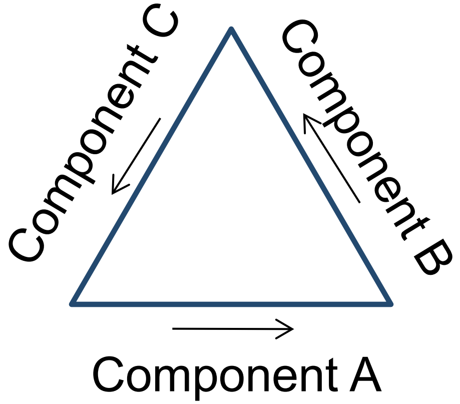


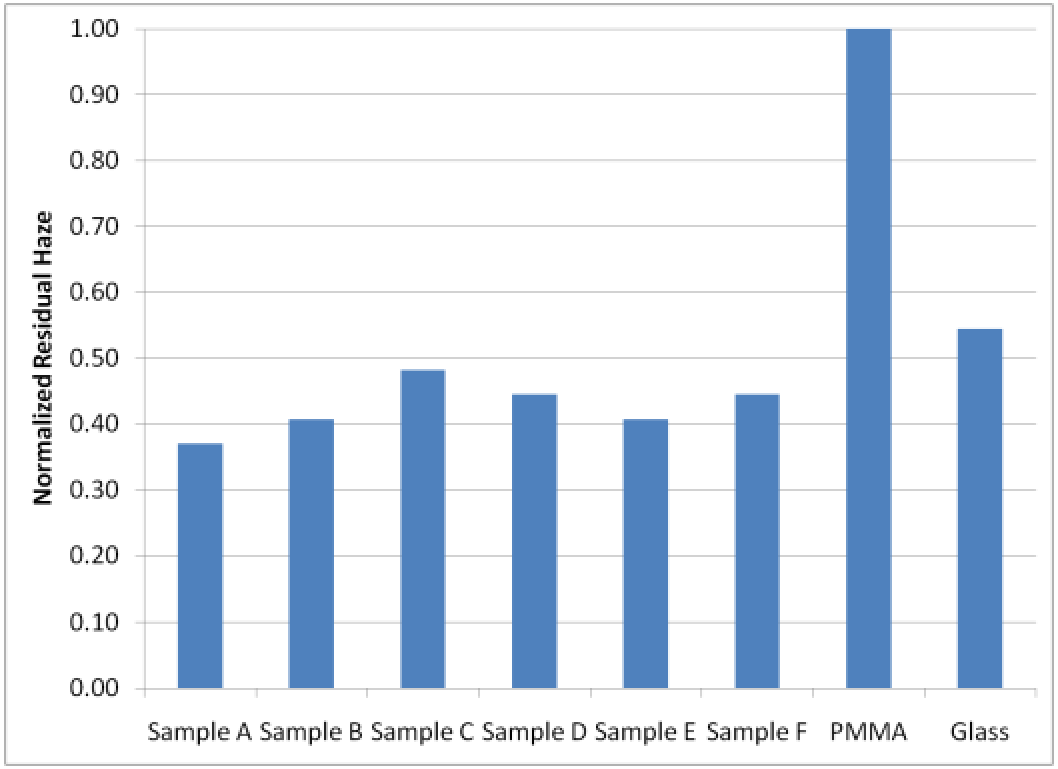
Hardcoated PMMA

Coatings can demonstrate significant improvement in surface durability and uniformity over acrylic surfaces

* 3M Proprietary Exposure Cycle

Key Accomplishments:
Coatings with Enhanced Cleanability





Additives may improve non-contact cleanability relative to PMMA
Retention past 4000 h of accelerated weathering

* 3M Proprietary Exposure Cycle

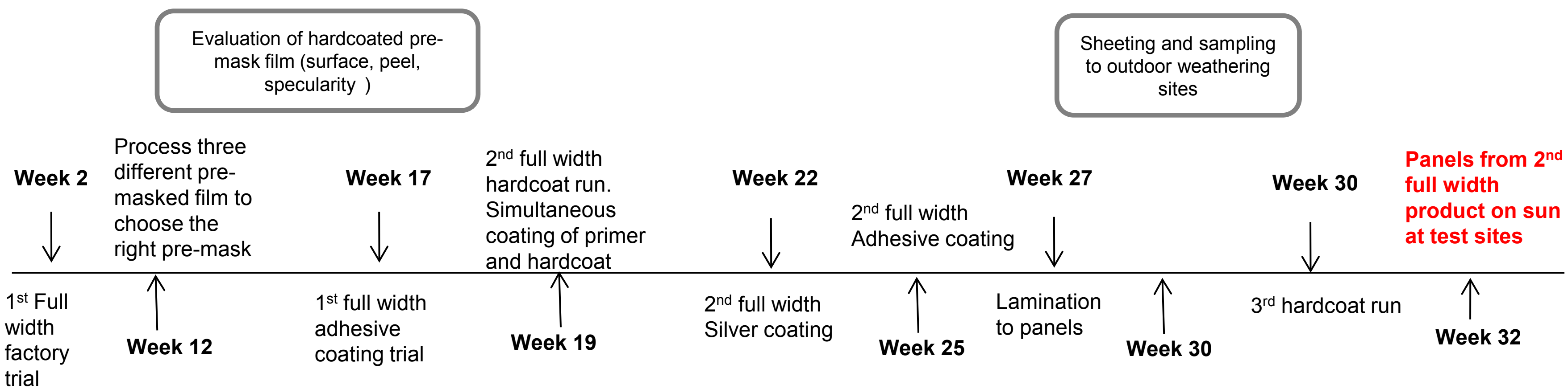
Weathering results on production material

Accelerated Weathering Feb 2013

Sample ID	Test	0 hrs	500 hrs	1000 hrs	1500 hrs	2000 hrs	2500 hrs	3000 hrs	Δ(final – initial)
101027-003	Specularity	93.7	93	93.1	93.4	92.8	93.1	92.7	-1
	THR	92.7	92.6	92.6	92.6	91.9	92.0	91.8	-0.9
101027-004	Specularity	94.2	94	93	93.3	92.9	93.0	92.7	-1.5
	THR	92.7	92.3	92.2	92.6	91.9	92.0	92.0	-0.7
Control	Specularity	94.3	94.1	93.7	NA	93.8	93.5	93.2	-1.1
	THR	94.4	93.9	93.6	NA	93.2	92.7	92.6	-1.8

Scale-Up

- Status
  - Successful scale-up to full width (49”)
  - Volume in thousands of linear yards
  - Post processing complete to laminates
- Challenges
  - Web handling
  - Pre-mask adhesion



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Hardcoat Project: Summary and Key Lessons

- Summary
  - We have successfully developed coating formulations which significantly increase the abrasion resistance of mirror films
  - We have demonstrated manufacturing scale-up of these films to full width and production volumes
  - Implementation of these films in commercial test sites is planned for Q2 2013 (Abengoa, Gossamer Space Frames)

- Key Lessons
  - Importance of testing and test design
  - Interaction effects in film construction
  - Lab to manufacturing – scale-up, details matter

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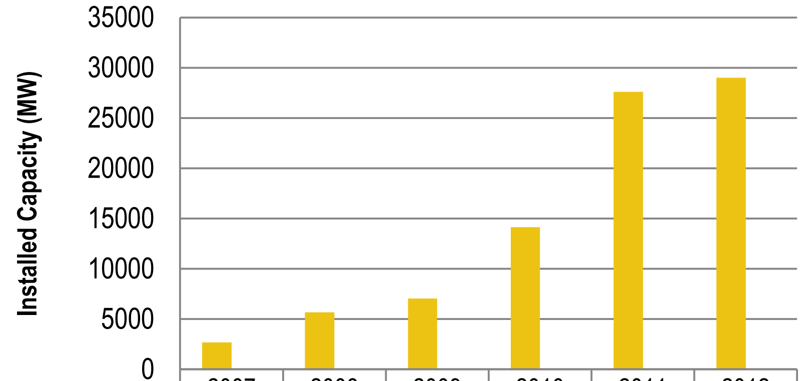
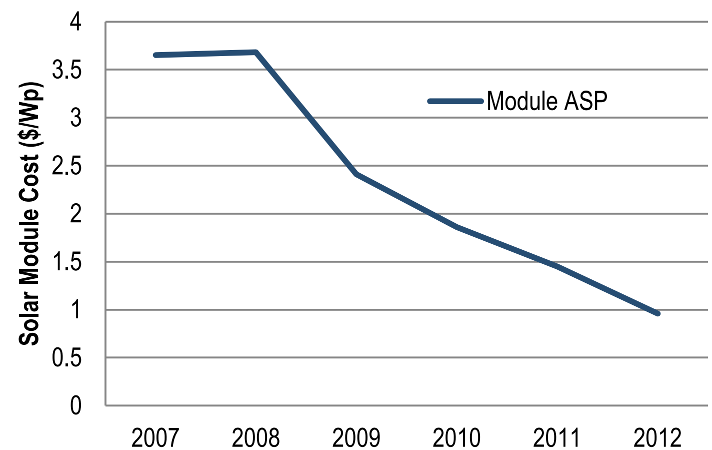
Background

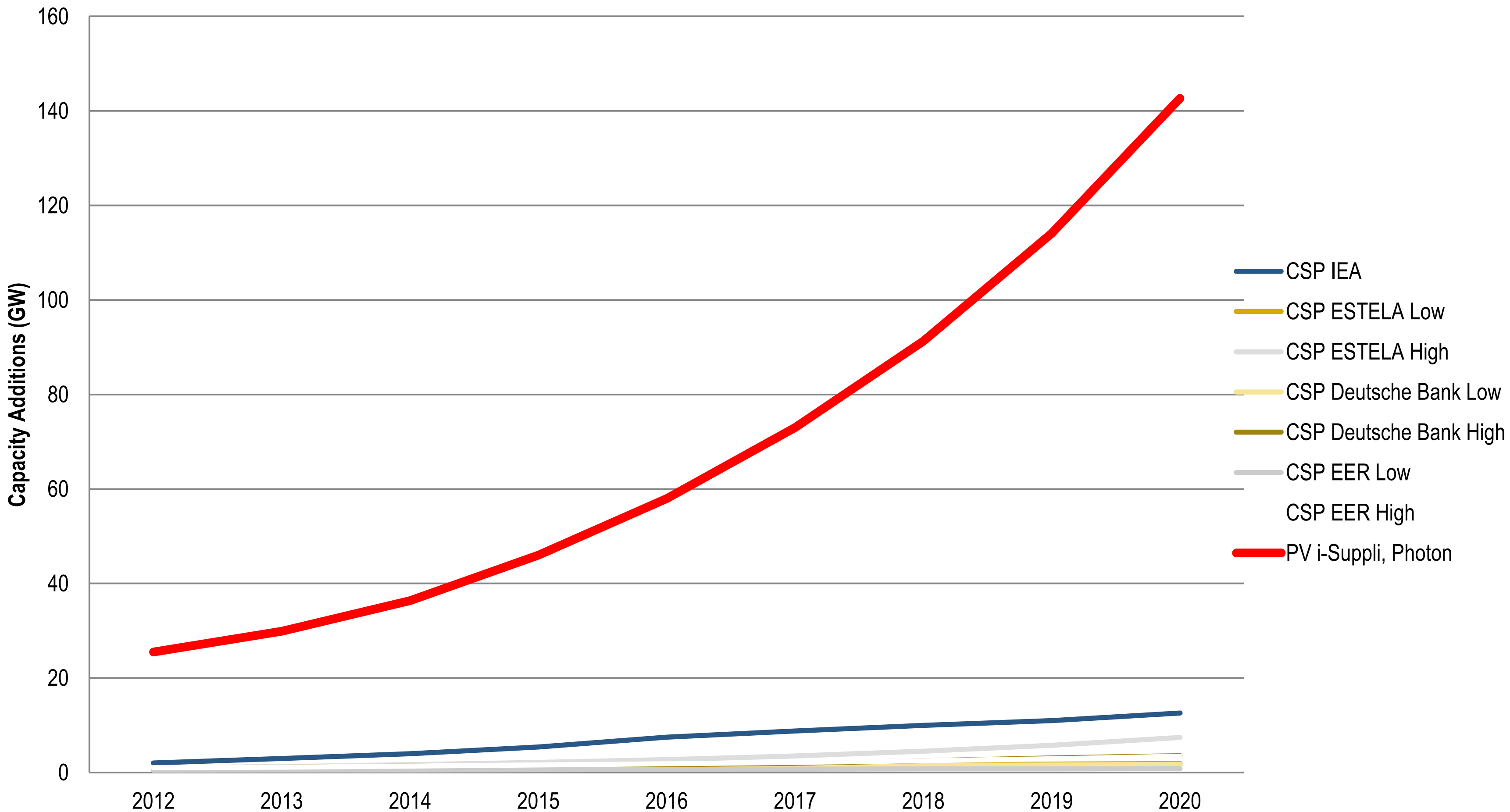
- High growth in new solar energy capacity, 10X increase since 2007
- PV dominant, over 90% share
- Cost reduction a key driver, over 70% reduction in PV module pricing since 2007
- CSP – dramatic cost reductions needed to remain competitive
- New solutions for the solar field a key opportunity



	2007	2008	2009	2010	2011	2012
MW	2674	5676	7059	14135	27600	29000
Module ASP	3.65	3.68	2.41	1.86	1.45	0.96



Solar Global Market Forecasts



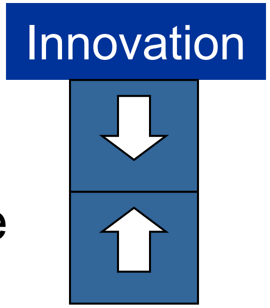
Positive outlook for solar energy in general, but current forecasts has CSP developing into a niche solution

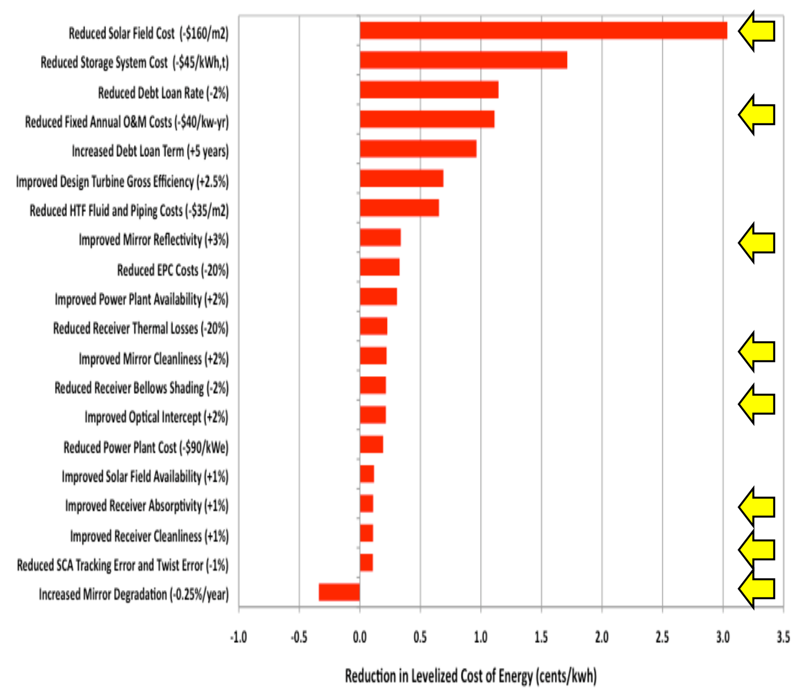
Opportunities for LCOE Reduction

- Lower costs
  - Novel designs – reduced materials
  - Lower cost components
  - Higher volume
  - Easier assembly
  - Reduced O&M costs

- Higher performance
  - Higher optical efficiency
  - Increased structural and shape accuracy
  - Higher operating temperature

$$\text{LCOE} = \frac{\text{Cost}}{\text{Performance}}$$





C. Kutscher, M. Mehos, C. Turchi, G. Glatzmaier, T. Moss, "Line-Focus Solar Power Plant Cost Reduction Plan" NREL/TP-5500-48175, December 2010

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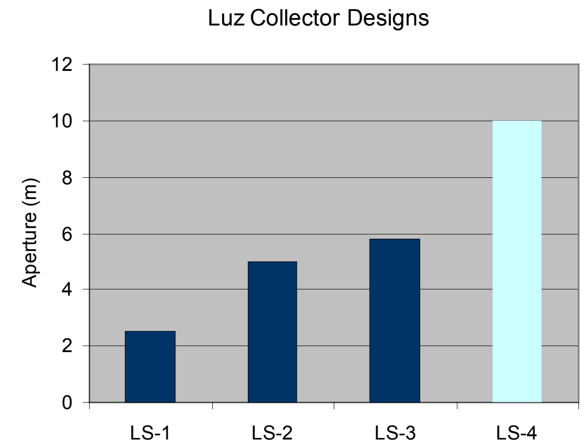
Glass mirror based solar collector

Film based solar collector

Large Aperture Parabolic Trough

- Increasing aperture size leverages other solar field fixed costs
- Luz designs envisioned up to 10m aperture (LS-4). Design had a capital cost target of <$3000/kWe [1]
- Flagsol Heliotrough, 15+% cost improvement for 6.8m aperture design [2]
- Kolb and Diver estimate up to 15% LCOE reduction going from 5 to 10 m aperture [3]



Power Plant Size	250 MW	
Heat Transfer Fluid	500 Hitec	
Thermal Storage	16 hours	
SCA Width [m]	5	10
SCA Area [m^2]	470.3	940.6
Average Focal Length [m]	1.8	3.6
Distance between Rows [m]	15	30
Field Aperture Area [m^2]	2,570,000	2,570,000
Total Plant Installed Cost	$1300 M	$1148 M
Annual Solar-Electric Efficiency	17.2%	18.3%
Annual Plant Capacity Factor	56%	60%
Nominal LCOE [$/kWh]	0.119	0.101
LCOE Improvement		15.1%

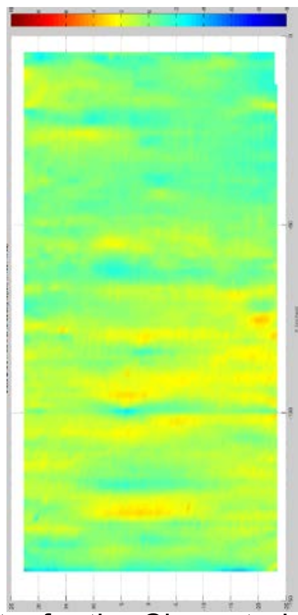
(1) P. de Laquill III, D. Kearney, M. Geyer, and R. Diver (in Solar Thermal Electric Technology, 1993)
(2) U. Herrmann, CSP Summit, San Francisco, 2010
(3) G. Kolb and R. Diver, SolarPaces 14, Las Vegas 2008

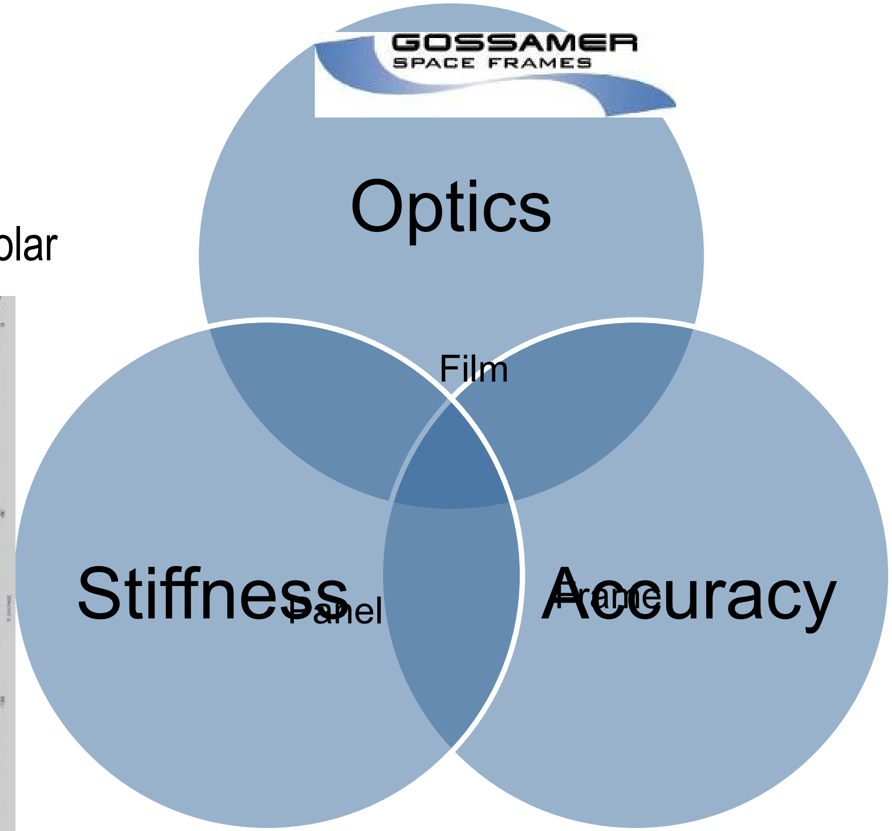
Larger aperture – an established means to reduce cost for parabolic trough CSP

Next Generation Solar Collector Design Approach

- Design Concept
  - Large Aperture parabolic trough
  - High concentration factor (100X +)
  - Increases productivity while minimizing solar field equipment

- Elements
  - Reflective film
  - Panel technology
  - Space frame





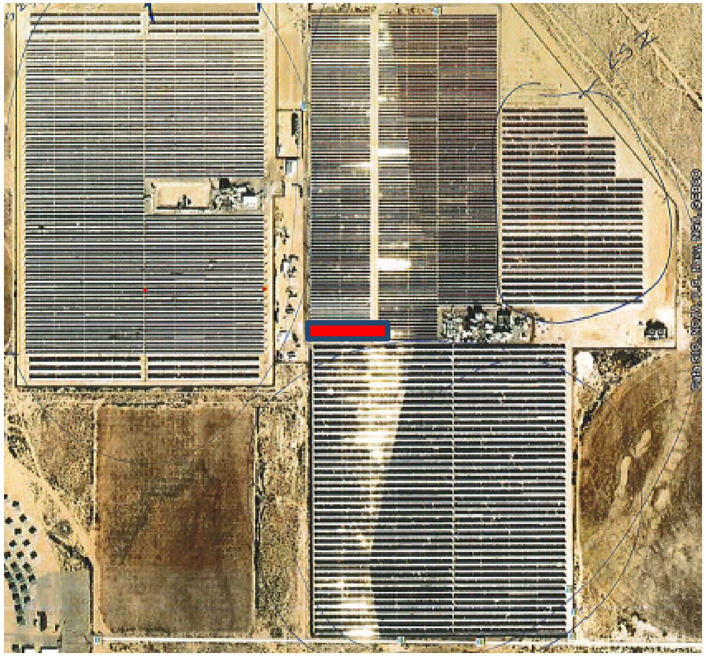
A. Molnar et al., "A Novel Geometry for the Characterization of Large Mirror-Film Based Panelized Reflectors," SolarPaces, Granada, Spain 2011

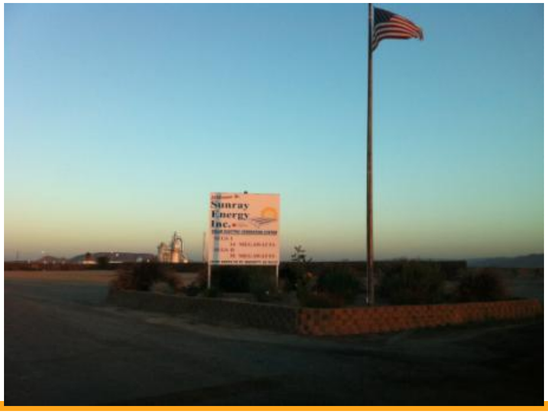
Integrated solution approach can address both cost reduction and performance improvement

Large Aperture Trough (LAT) Demonstration Loop

- Description
  - Solar Collectors : 12m x 7.3m
  - Concentration Factor: 103
  - Loop: 16 solar collectors
  - Output: 840 kWt / 275 kWe

- Location
  - Plant: SEGS I
  - Location: Daggett, CA
  - Host: Cogentrix





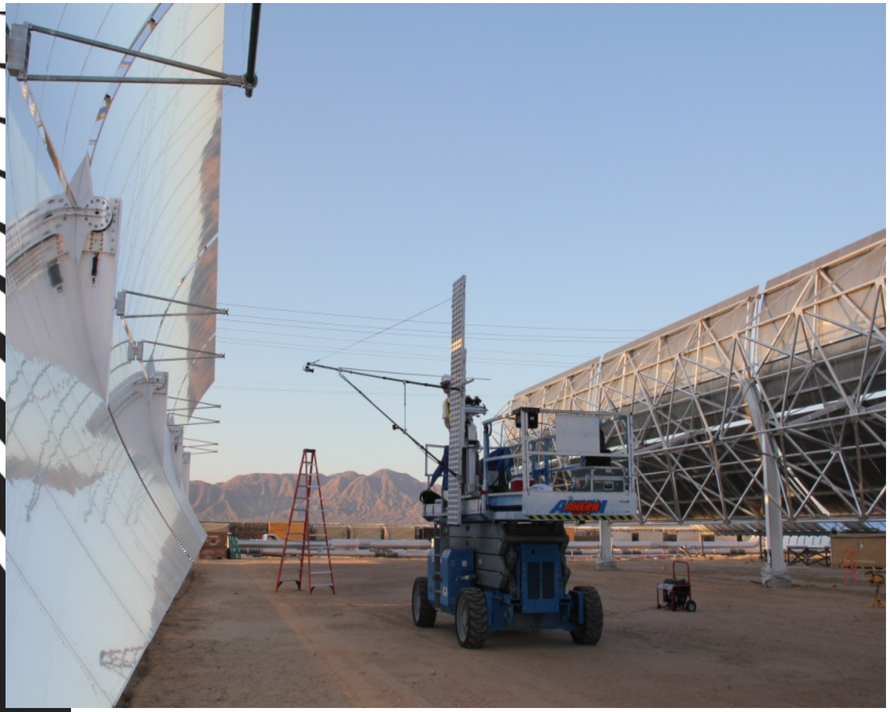
Test Loop – SEGS I


Large Aperture Trough (LAT)
Engineered by Gossamer Space Frames and 3M

Parabolic Trough Demonstration Loop
Aperture 7.3m
Concentration factor 103

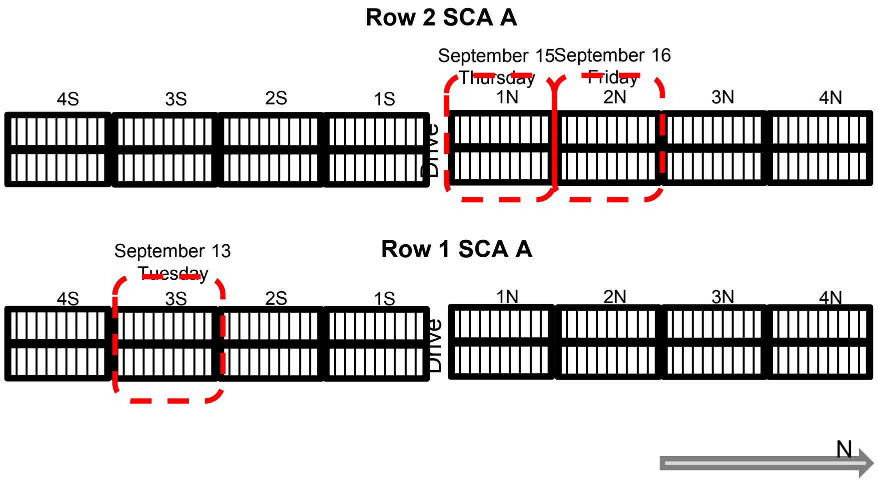
Host
SEGS I - Cogentrix
Daggett, CA (Mohave Desert)

NREL Field Deployed VSHOT

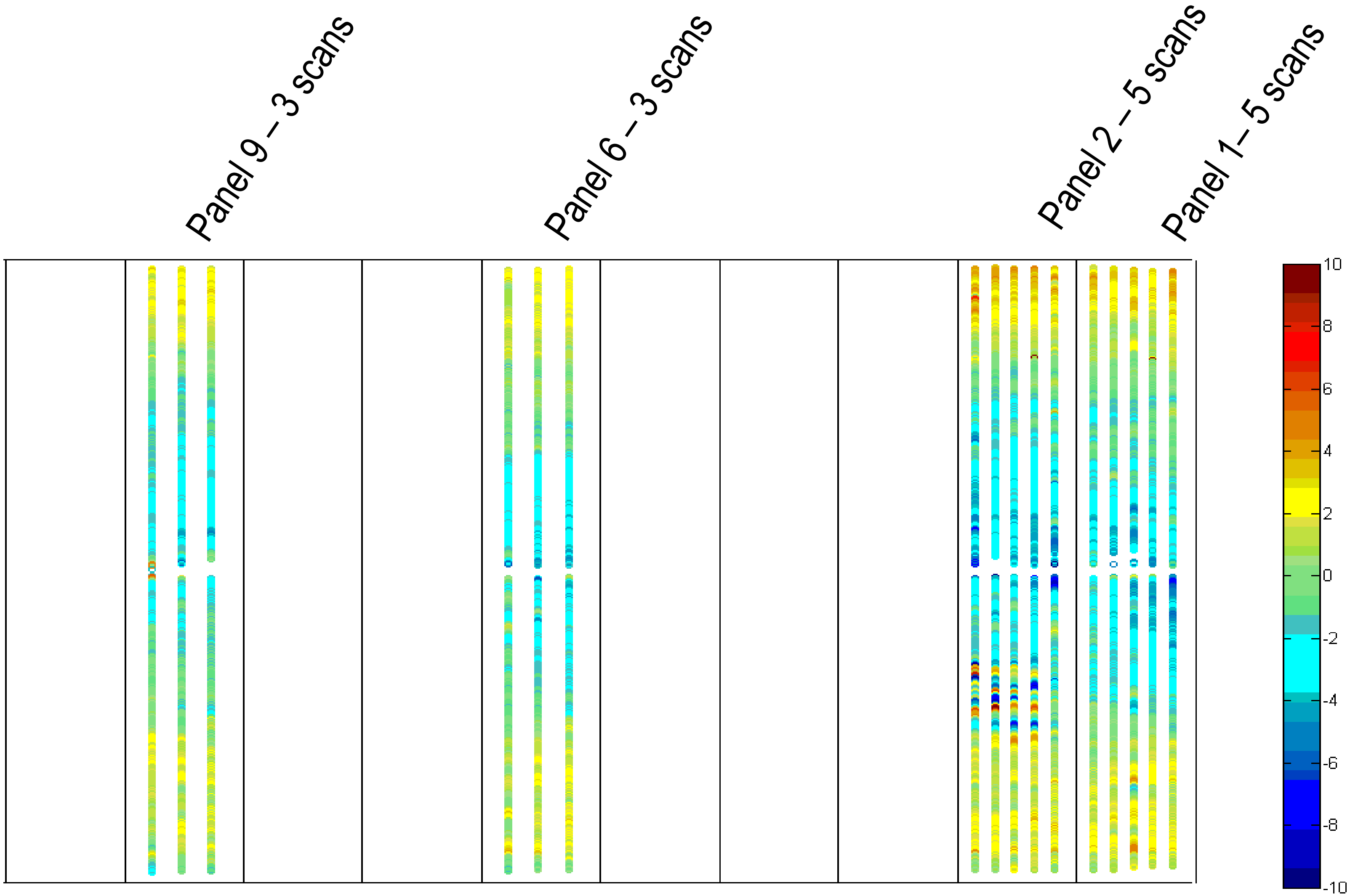


Assumptions

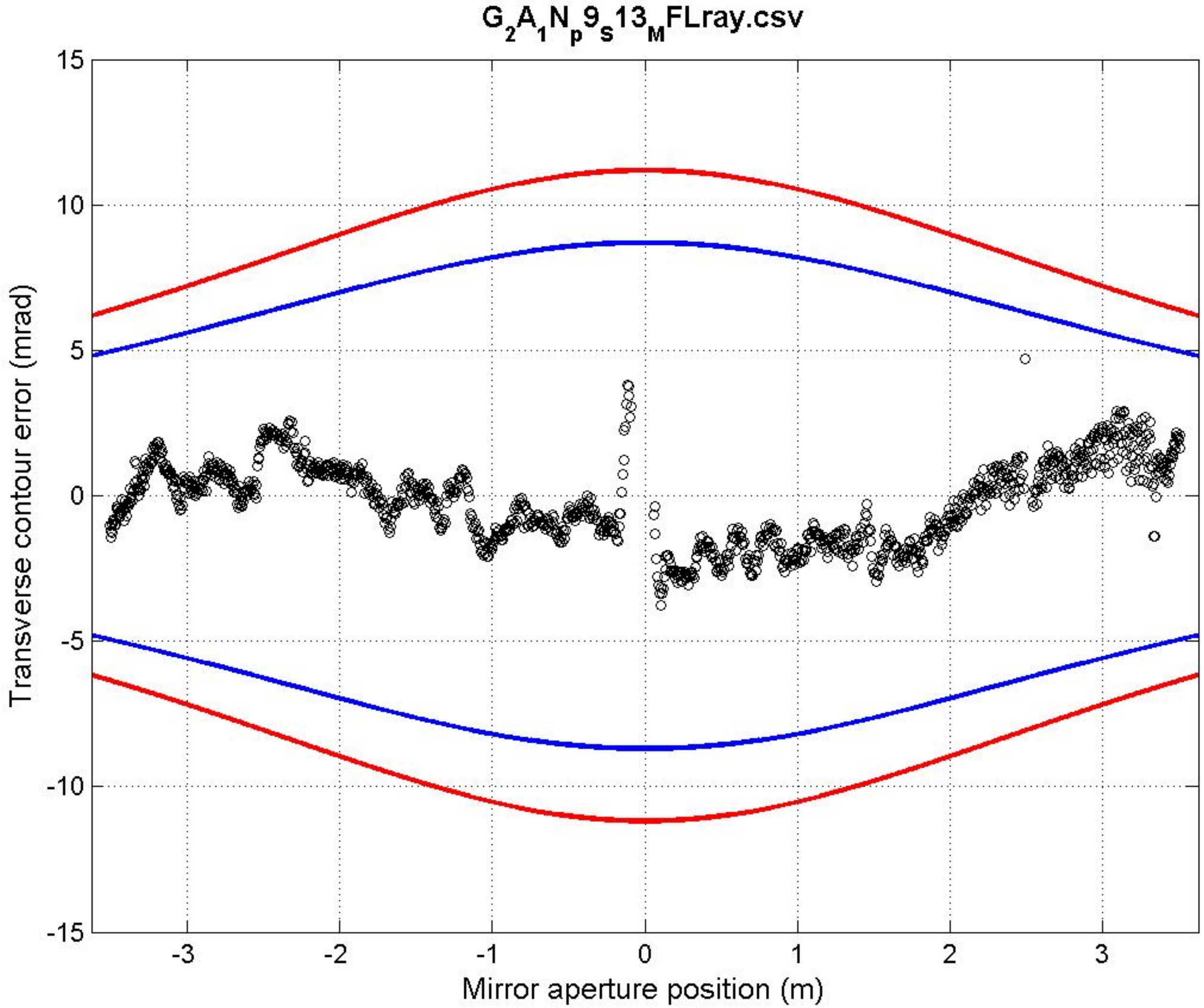
- Errors in the longitudinal direction are neglected.
- The reflective surface has perfect specular reflectance.
- The receiver tube has 100% absorbance.
- A 70 mm receiver tube is modeled without a glass envelope.
- DLR-measured sun shape is used as the source.
- 49,000 rays normal to the aperture are traced.



VSHOT Example Results

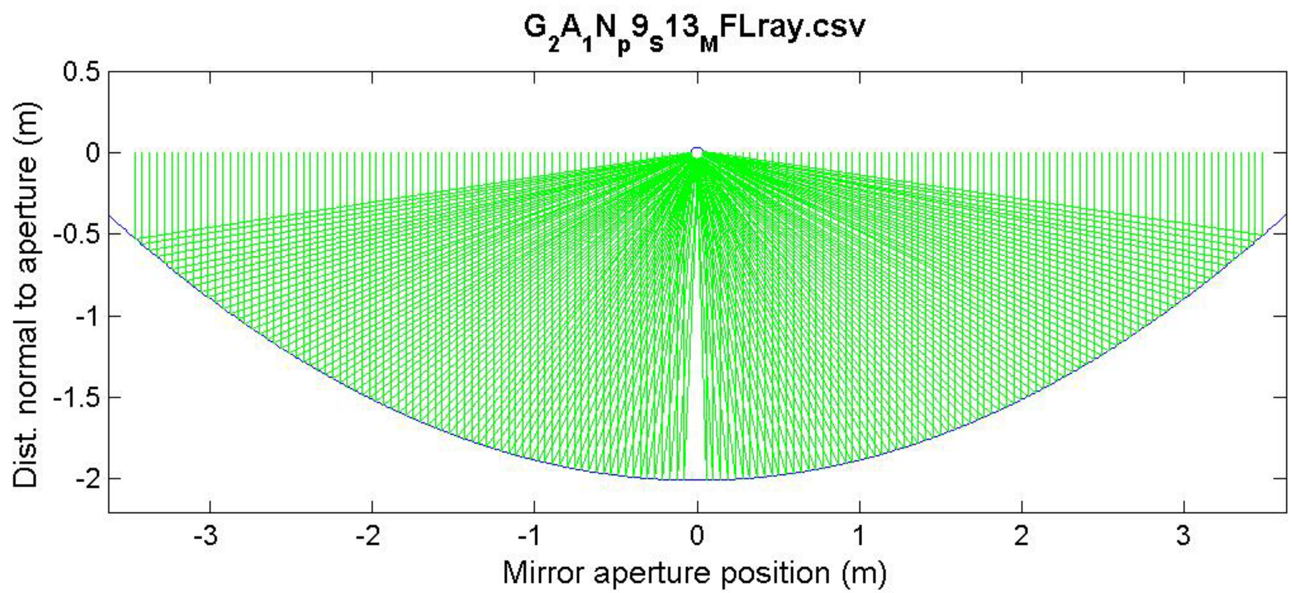


Example Acceptance Window Plot



VSHOT Summary Results

SCE	Build Type	Average RMS Slope error (mrad)	Maximum RMS Slope error (mrad)	Minimum RMS Slope error (mrad)	Average Intercept Factor
1A 3S	Standard	3.60	4.22	3.31	95.20%
2A 1N	Modification 1	2.45	3.51	1.45	98.80%
2A 2N	Modification 2	2.27	2.77	1.74	99.30%

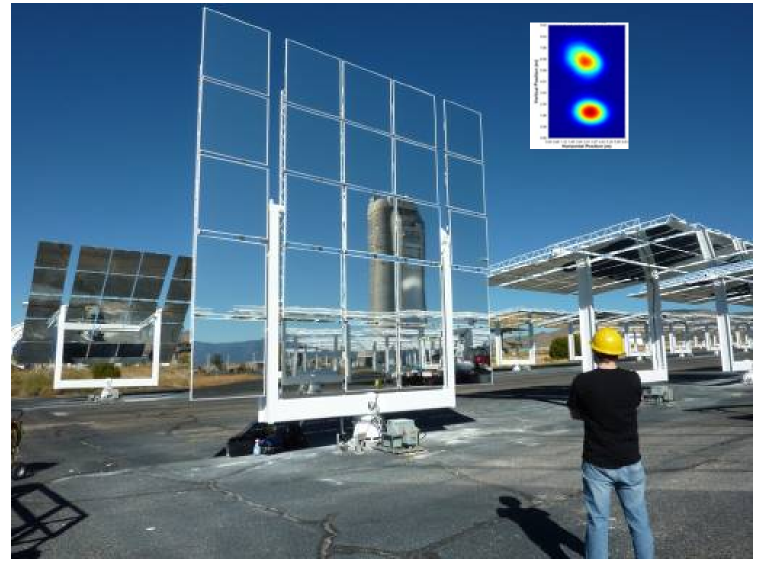


8m Aperture Trough

Courtesy: G. Reynolds, Gossamer Space Frames

Mirror Films: Heliostat Applications

- Background
  - Work driven by Sandia National Labs (Cliff Ho)[1]
  - Mirror films typically not thought of as feasible for long focal range designs



- Objectives
  - Determine feasibility of mirror based heliostats
  - Explore new heliostat design options with mirror films

Figure 2. Left: Map showing the locations of the single-facet beam tests at 525 m and 1733 m away from the long-range heliostat target (LRHT). Right: Rig used to hold and track the facets.

“Characterization of Metallized Polymer Films for Long-Distance Heliostat Applications,
C. Ho, J. Sment, J. Yuan, C. Sims, SolarPACES 2012, Marrakech, Morocco, Sept 2012

Comparison: Glass vs Mirror Film Facets

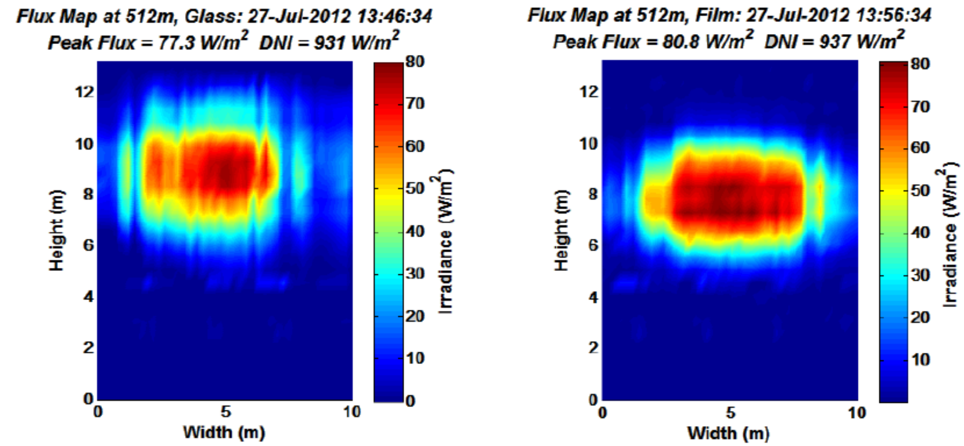


Figure 5. Measured irradiance distribution at ~500 m from the silvered glass facet (left) and the SMF1100 facet (right). The peak flux in both cases is ~80 W/m^2.

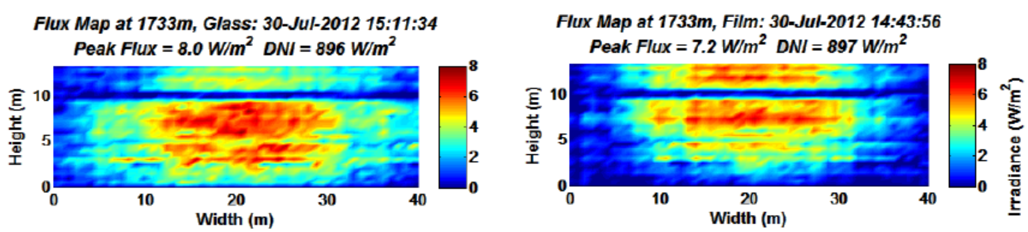
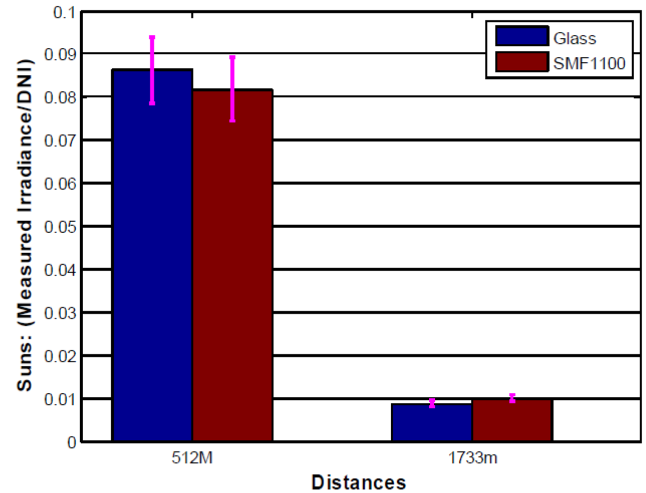


Figure 8. Measured irradiance distribution at ~1700 m from the silvered glass facet (left) and the SMF1100 facet (right). The peak flux in both cases is ~7-8 W/m^2.



Current commercially available reflective films have potential for long focal length applications

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Conclusions

- CSP
  - Solar Energy growing into a significant energy source globally (10X growth in 5 years)
  - CSP needs dramatic cost reduction in order to remain relevant
- Mirror Films
  - Mirror films enable new design space in solar collectors
  - Larger aperture parabolic trough collectors offer opportunity for cost reduction – reduced to practice at demonstration loop level
  - Feasibility of mirror films for long distance heliostats demonstrated
- Future Work (DE-EE005795 – 3M / Gossamer / Sandia / NREL)
  - New reflective films with higher SWTHR and specular reflectance
  - Advanced heliostat and solar collector design

Acknowledgments

Cogentrix – S. Frymeyer, K. Anderson, R. Lawerence, K., Koele

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Sandia National Lab - Cliff Ho

3M – R. Charles, S. Clear, D. Hart, A. Molnar, E. Peterson, T. Solin


감사합니다
Natick
Grazie
Danke
Ευχαριστίες
Dalu
Obrigado
Thank You
Köszönöm
Tack
Спасибо
Dank
Gracias
谢谢
Merci
Seé
ありがとう

3M ECP 305+ Long Term Outdoor Exposure (NREL)