

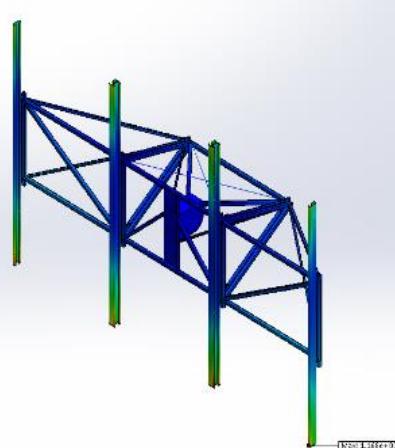


SOLARSTROM FÜR 6 CENT/KWH:

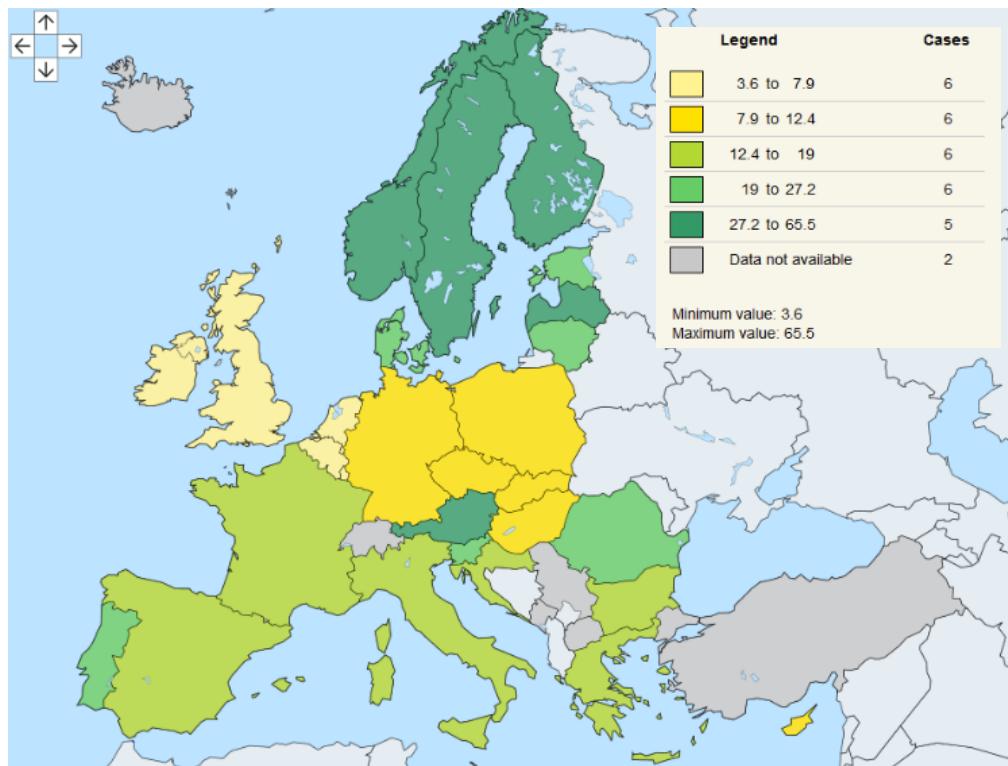
JPL

Jet Propulsion Laboratory
California Institute of Technology

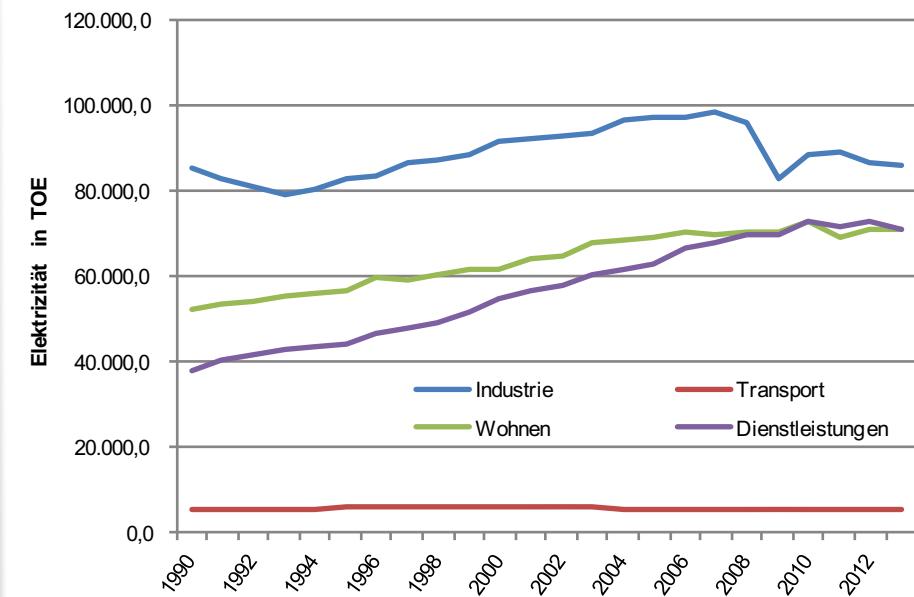
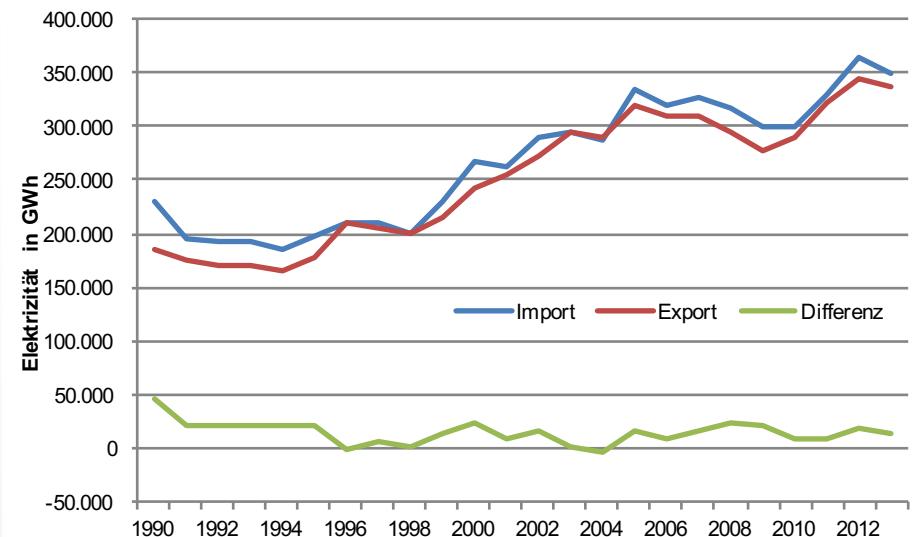
ENTWICKLUNG EINES LOW-COST HELIOSTATEN MIT DÜNNFILMREFLEKTORAM NASA JET PROPULSION LABORATORY



Ausgangssituation



Zum ersten Mal in der Geschichte der EU stellen erneuerbaren Energien mit einem Nettoenergieertrag von 890 TWh (27,2%) den größten Anteil dar

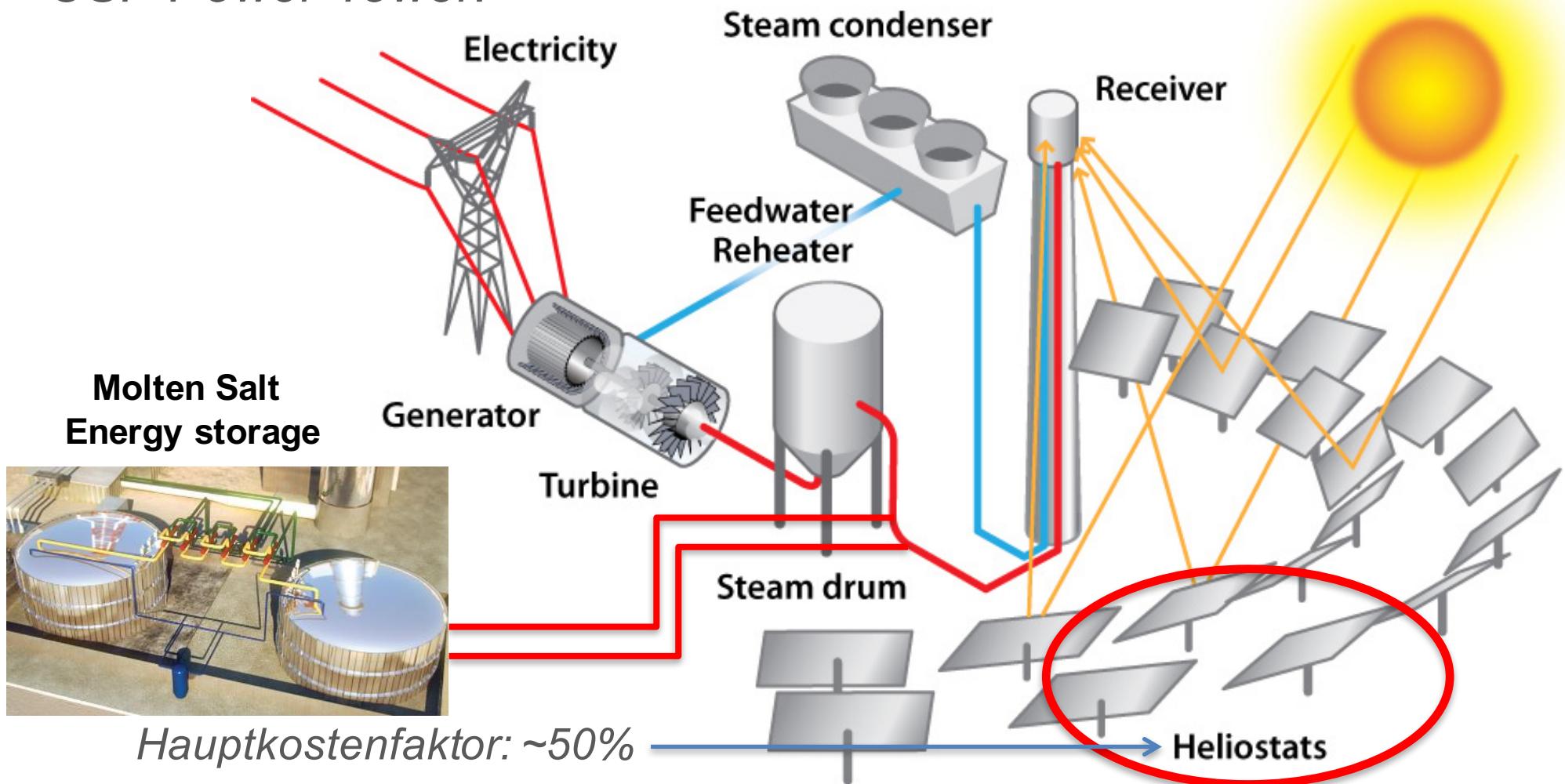


DOE SunShot Initiative



→ Solarstrom um 6 cent /kWh

CSP Power Tower:



4

DOE SunShot Initiative

JPL DSN Antenne

**JPL**

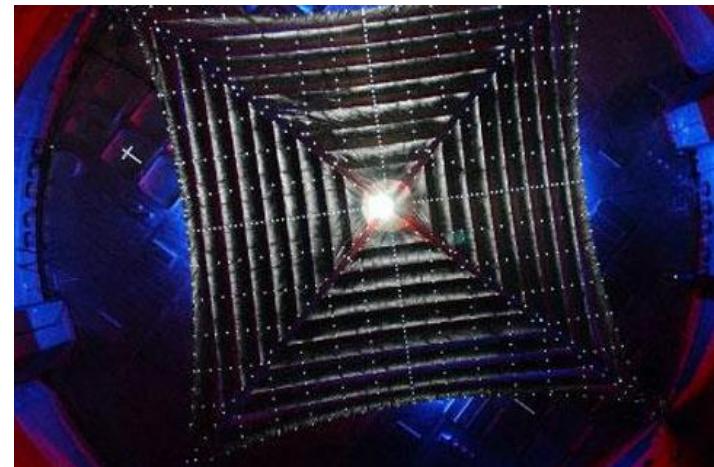
Jet Propulsion Laboratory
California Institute of Technology



Innovative Heliostaten

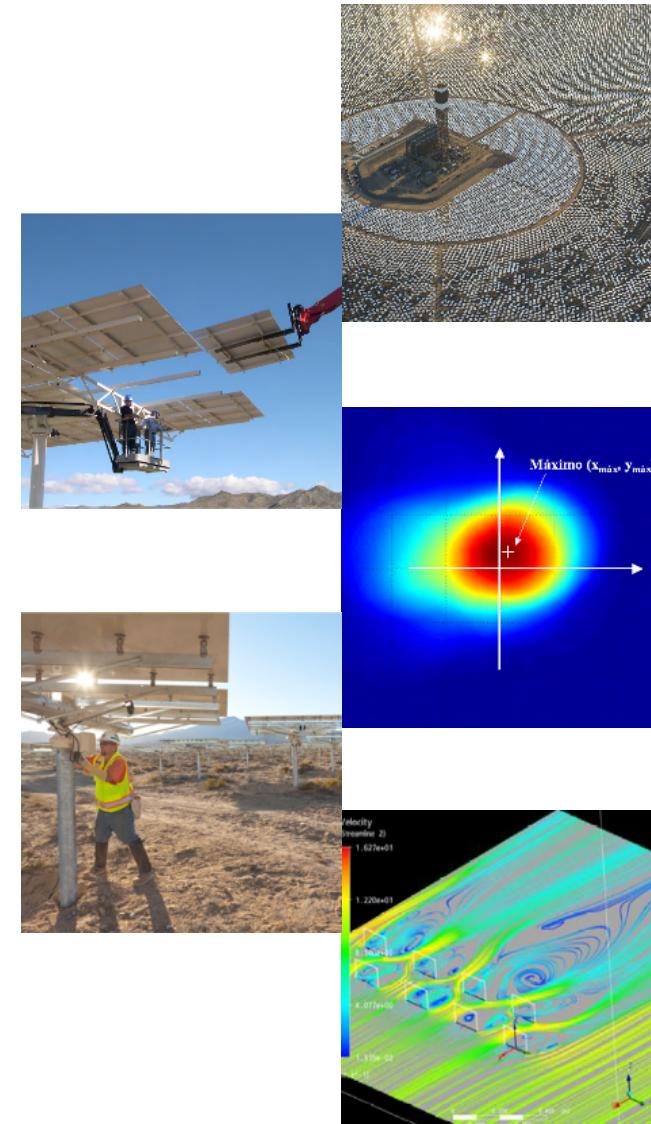
 **SunShot**
U.S. Department of Energy

L'Garde Solar Sail

**L·GARDE**
SMART SPACE TECHNOLOGY

Herausforderungen beim Heliostat-Design

- *Kosten (!)*
- *Herstellung/Assemblierung*
- *Optische Genauigkeit*
- *Lebensdauer und Wartung*
- *Hohe Windlasten*

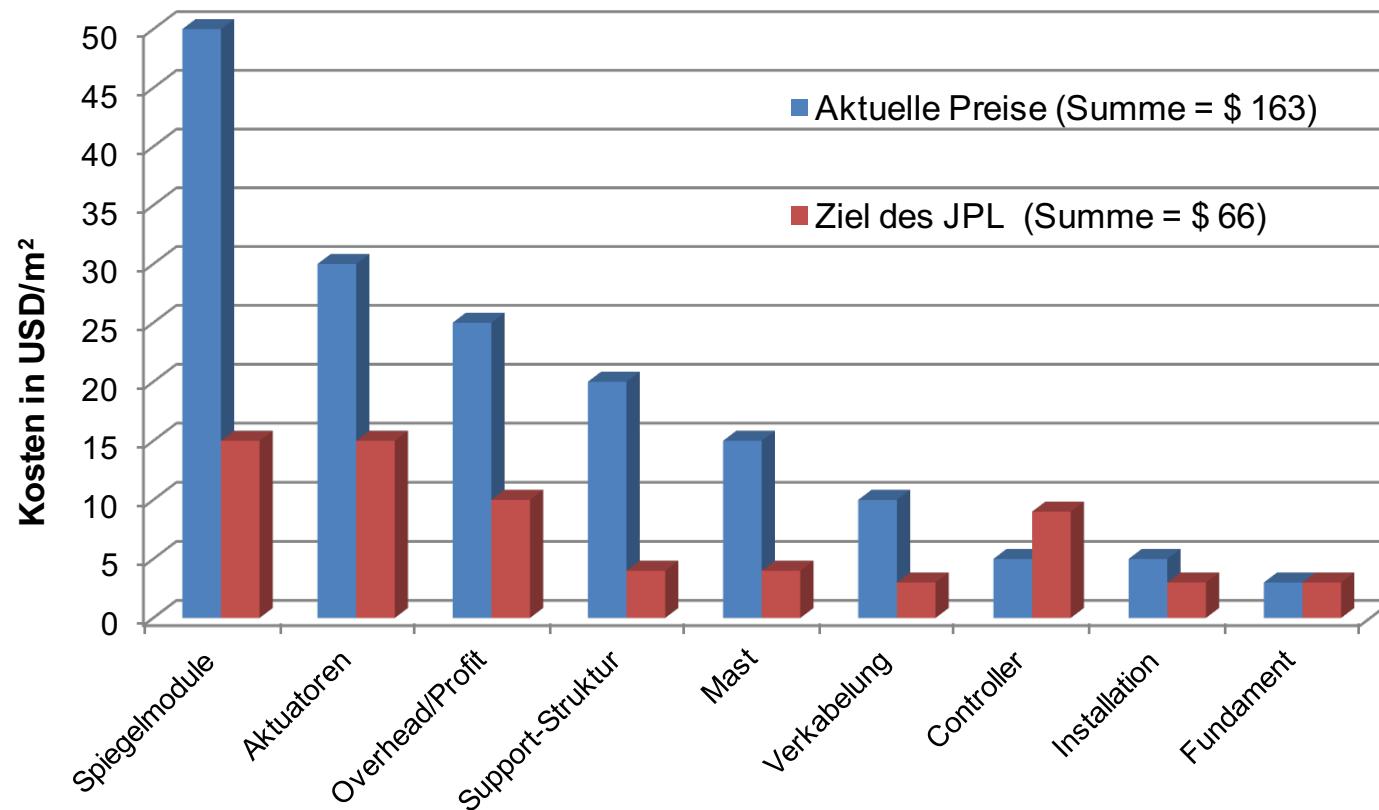


Kostenanalyse / Potentialerhebung

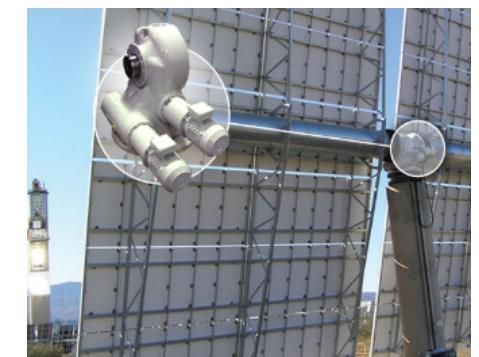
Grundlage: 100000 Stück/Jahr über 5 Jahre!

→ Größtmögliche Kostenreduktion:

1. Spiegel, 2. Aktuatoren, 3. Gerüst



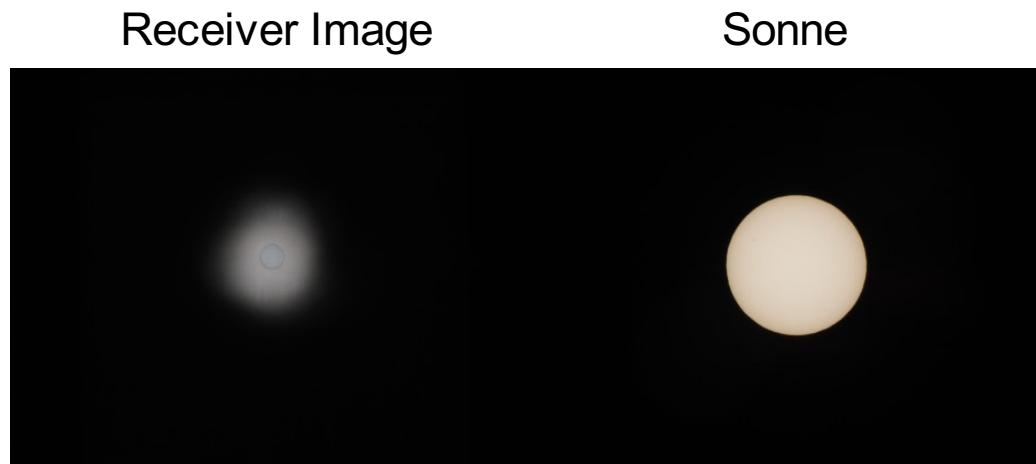
Um 6 cent/kWh zu erreichen → \$ 100/m² erforderlich!



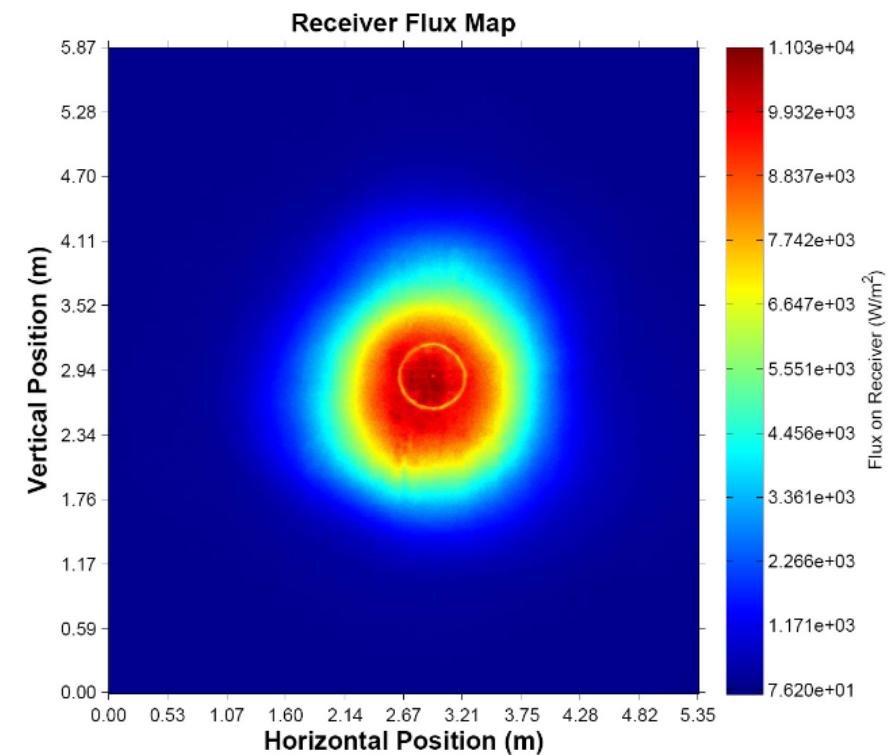
1. Heliostat Spiegel

Anforderungen:

- Hohe Reflexion im relevanten Wellenlängenbereich
- Hohe optische Güte:
 - Ebenheit / „RMS Slope Error“
 - Geringe Spekularität
- Hohe Steifigkeit
- Geringes Gewicht
- UV- und Wetterbeständigkeit



Clifford K. Ho and Siri S. Khalsa, ASME Proceedings 2001

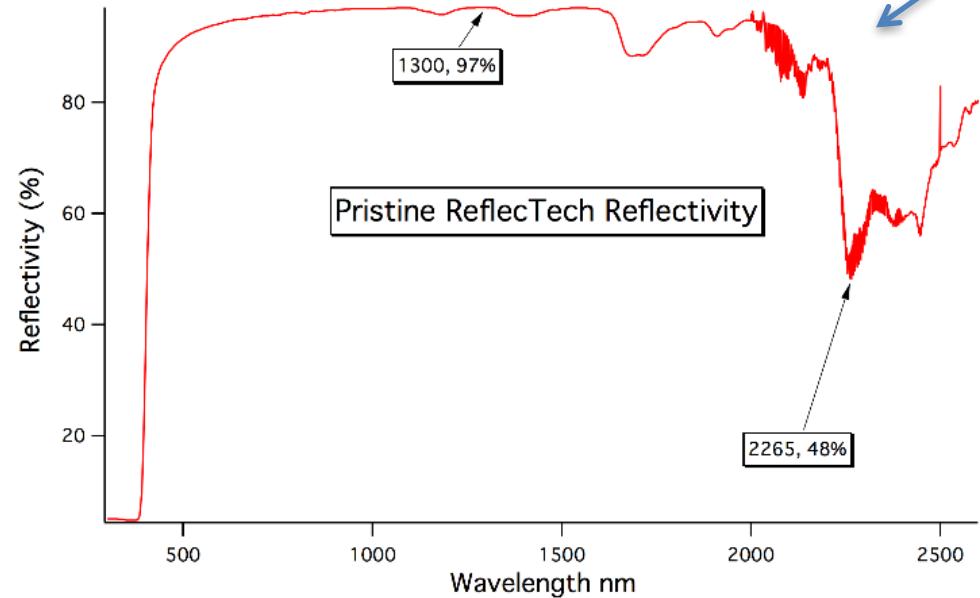


Float Glass Alternative

ReflecTech (versilberter Polymerfilm)

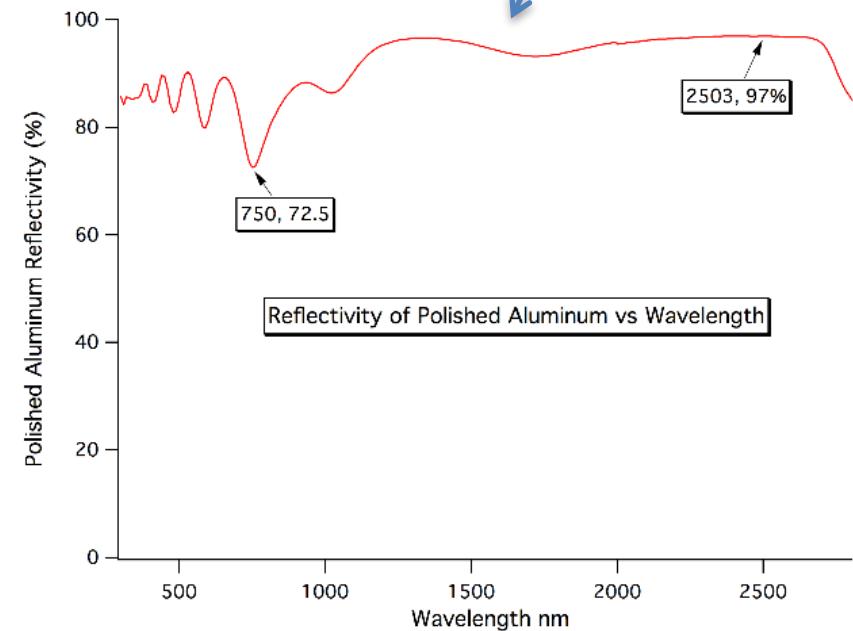
vs.

Eloxiertes Aluminium



ReflecTech Baseline Film:

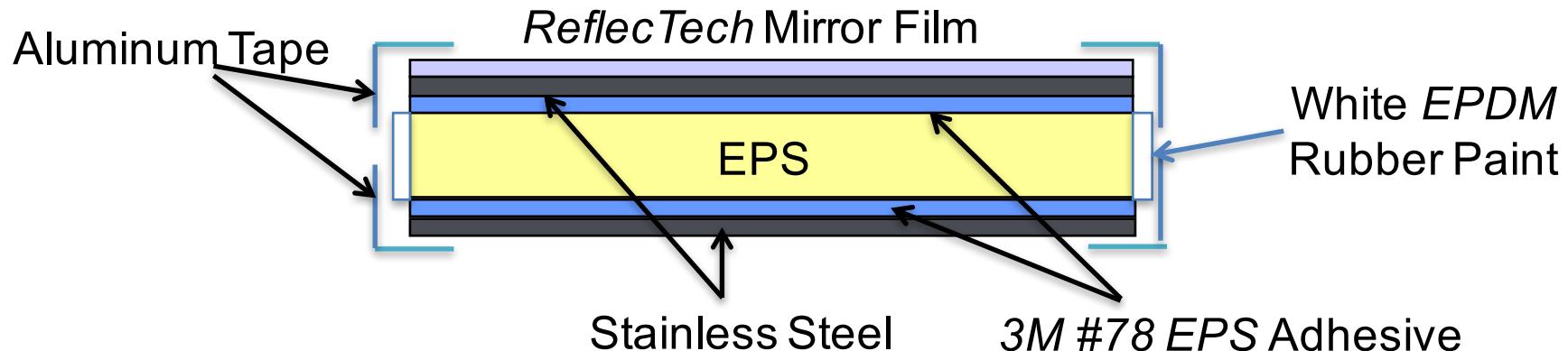
Durchschnittlicher Reflexionsgrad = 94%
(zwischen 300 nm und 2500 nm)



Polished Aluminum Film:

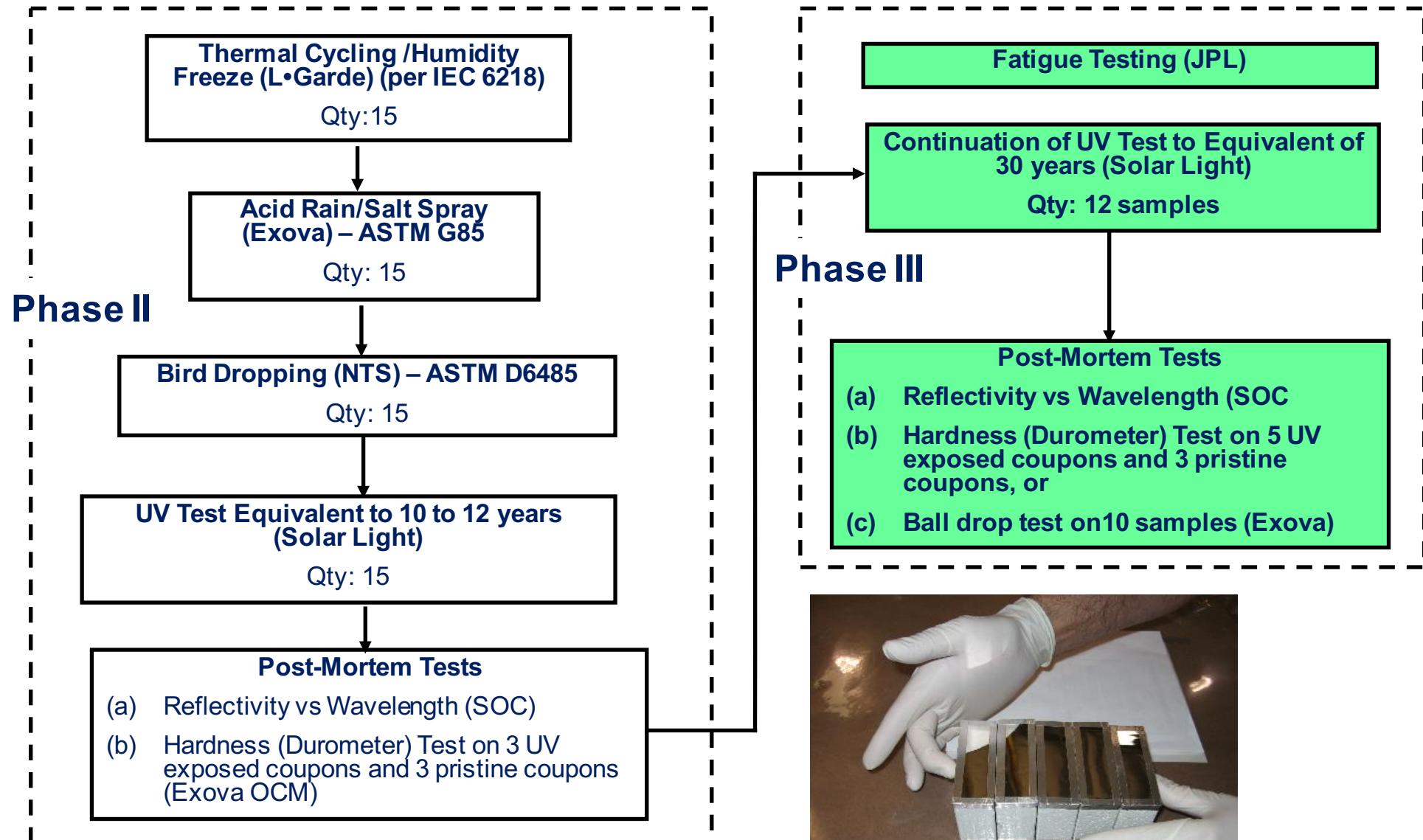
Durchschnittlicher Reflexionsgrad = 87%
(zwischen 300 nm und 2500 nm)

Spiegelpaneel in Sandwichbauweise



- EPS (*Extruded Poly Styrene*) wurde aus Kostengründen gegenüber PU bevorzugt
- EPS Schaum-Substrat mit 0.2 mm Edelstahlblech auf jeder Seite
- Edelstahlblech mittels 3M #78 EPS foam adhesive auf EPS verklebt
- 0,1 mm starker ReflecTech mirror film auf Vorderseite (Edelstahlblech) verklebt
- Seitenkanten mit 0,8 mm starker, wetterbeständiger weißer EPDM Gummischicht
- Aluminium Tape schützen den Übergang zwischen ReflecTech mirror film und EPS-Kleber, sowie EPDM Gummischicht von Umwelteinflüssen.
- 15 Test Coupons mit identem Aufbau wurden gefertigt und getestet

Spiegelpaneel in Sandwichbauweise



2. Heliostat Support-Struktur

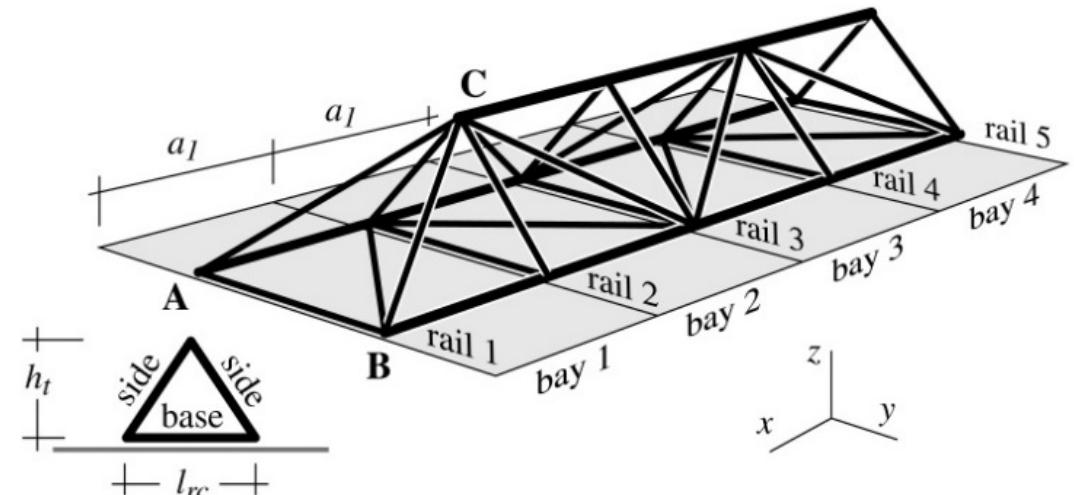
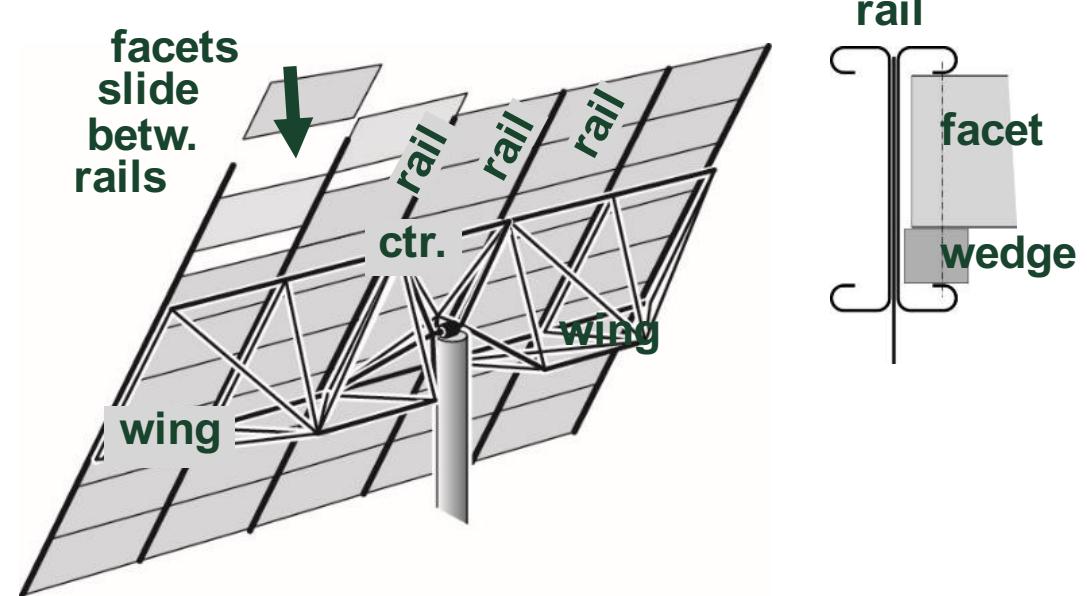
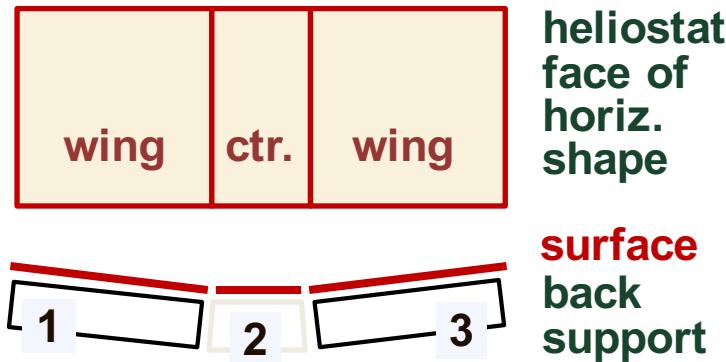
Anforderungen:

- Hohe Steifigkeit
- Einstellbarkeit (*Canting, Focusing*)
- Geringe Kosten
- Einfacher Transport
- Einfache Montage vor Ort
- **Summe: Winkelfehler < 5,8 mrad!**



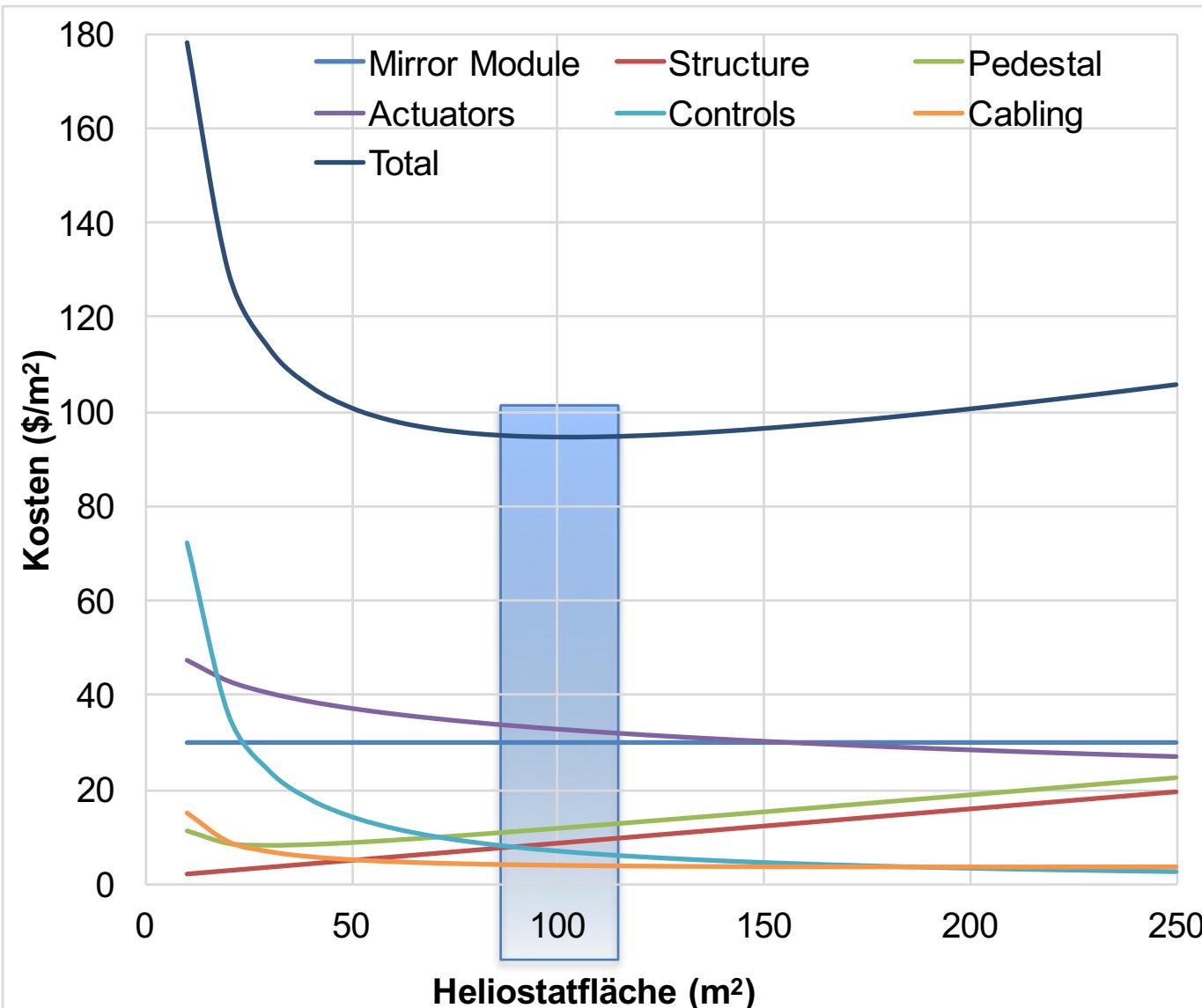
Konzept der mechanischen Struktur

Structure fabricated in three units: 1, 2, 3



simplest “standard” truss: mounted as wing at rear end

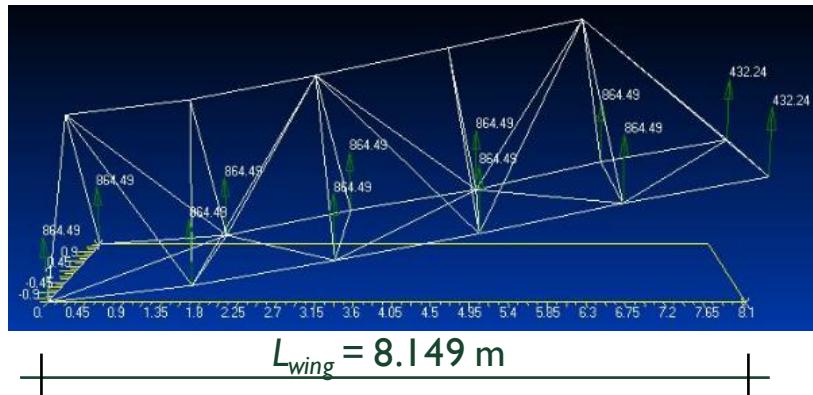
Kostenoptimales Heliostat-Sizing



- Nichtlinearität durch aerodynamische Effekte begründet
- Kosten abhängig von Materialwahl und Fertigungsverfahren
- Minimum zeichnet sich im Bereich um 100m² ab

Mechanische Struktur: Nachgiebigkeit

- ✓ Direct solution with energy method
 - ✓ FEA with NE/NASTRAN
- } for mutual control



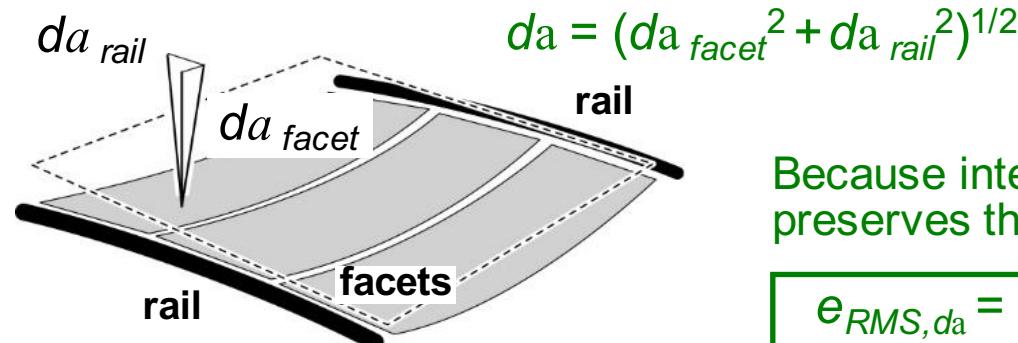
Tip deflection (average
for the two tip nodes)

- direct sol. 9.972 mm → 1.22 mRad
- FEA 9.968 mm

< 1.62 mRad budgeted for
truss deformations

First-order slope error estimate

- ✓ 4.86 mrad → $1/3$ (1.62 mrad) truss + $2/3$ (3.24 mrad) facet & rails
- ✓ $3.24 / \sqrt{2} = 2.291 \text{ mRad}$ for each of facet & rail deformations (orthogonal)



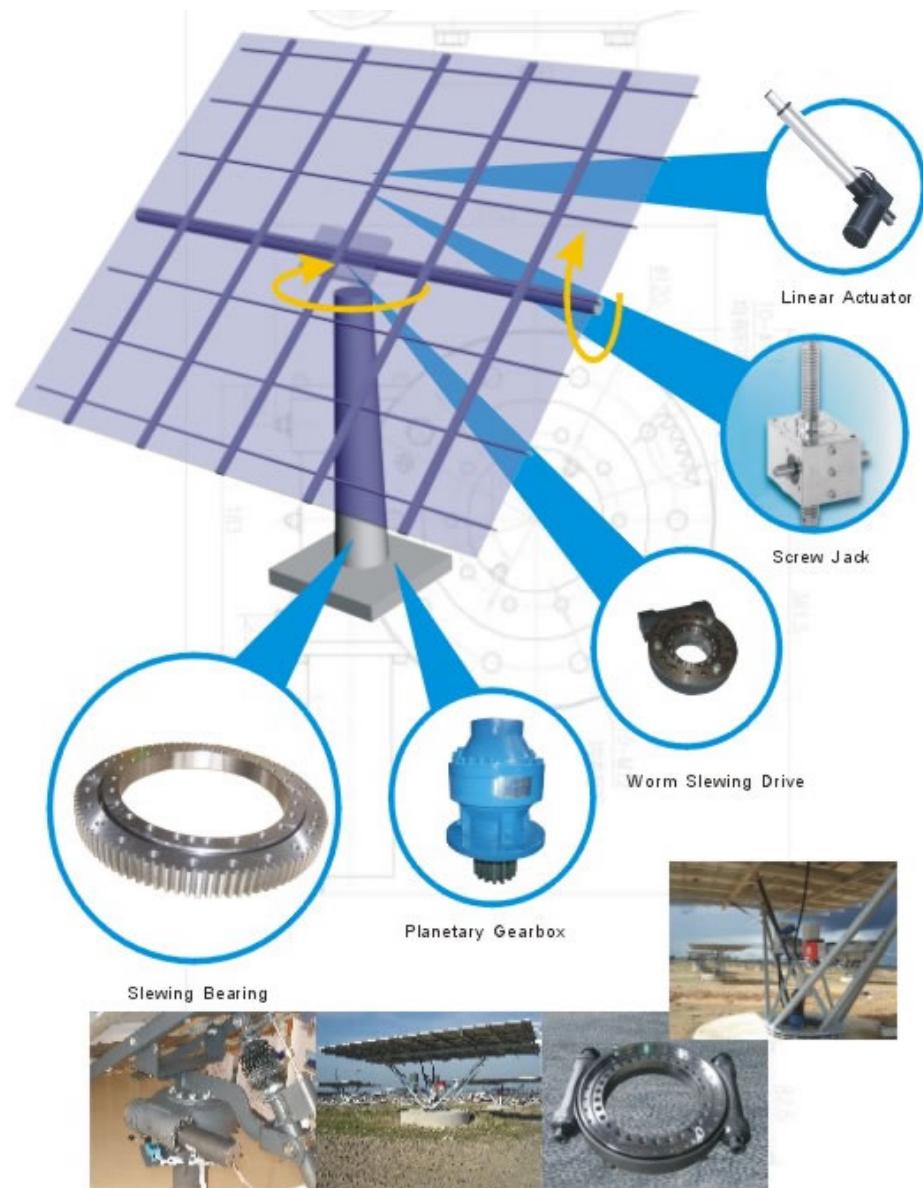
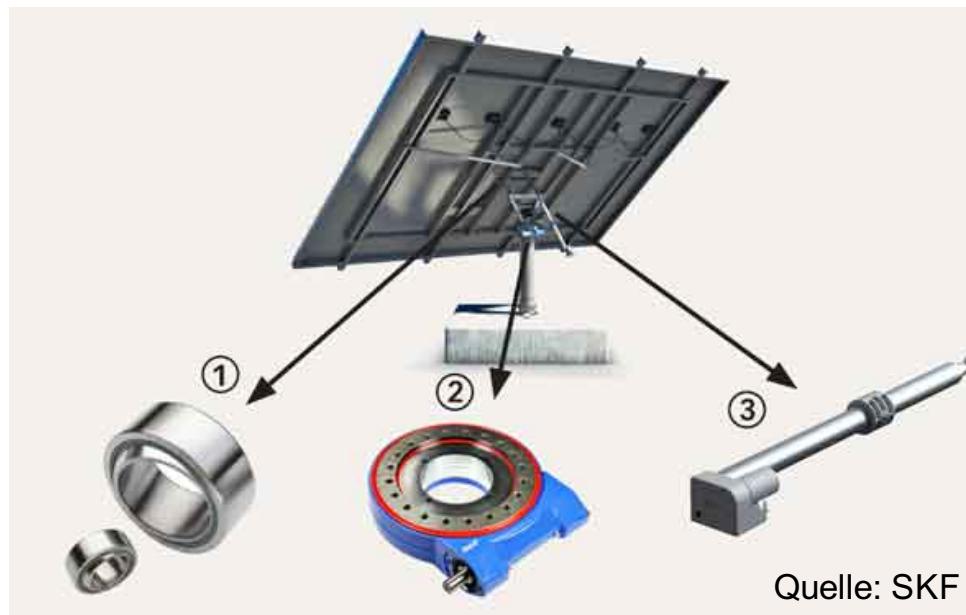
Because integration in this context
preserves the orthogonal relation, ...

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

3. Heliostat Aktuatoren

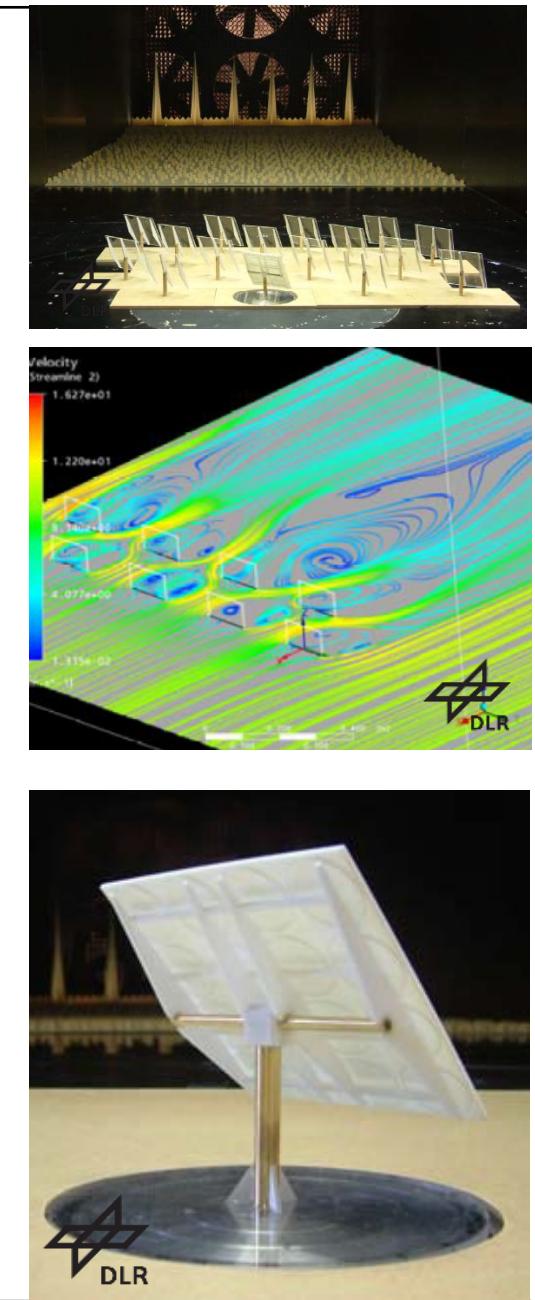
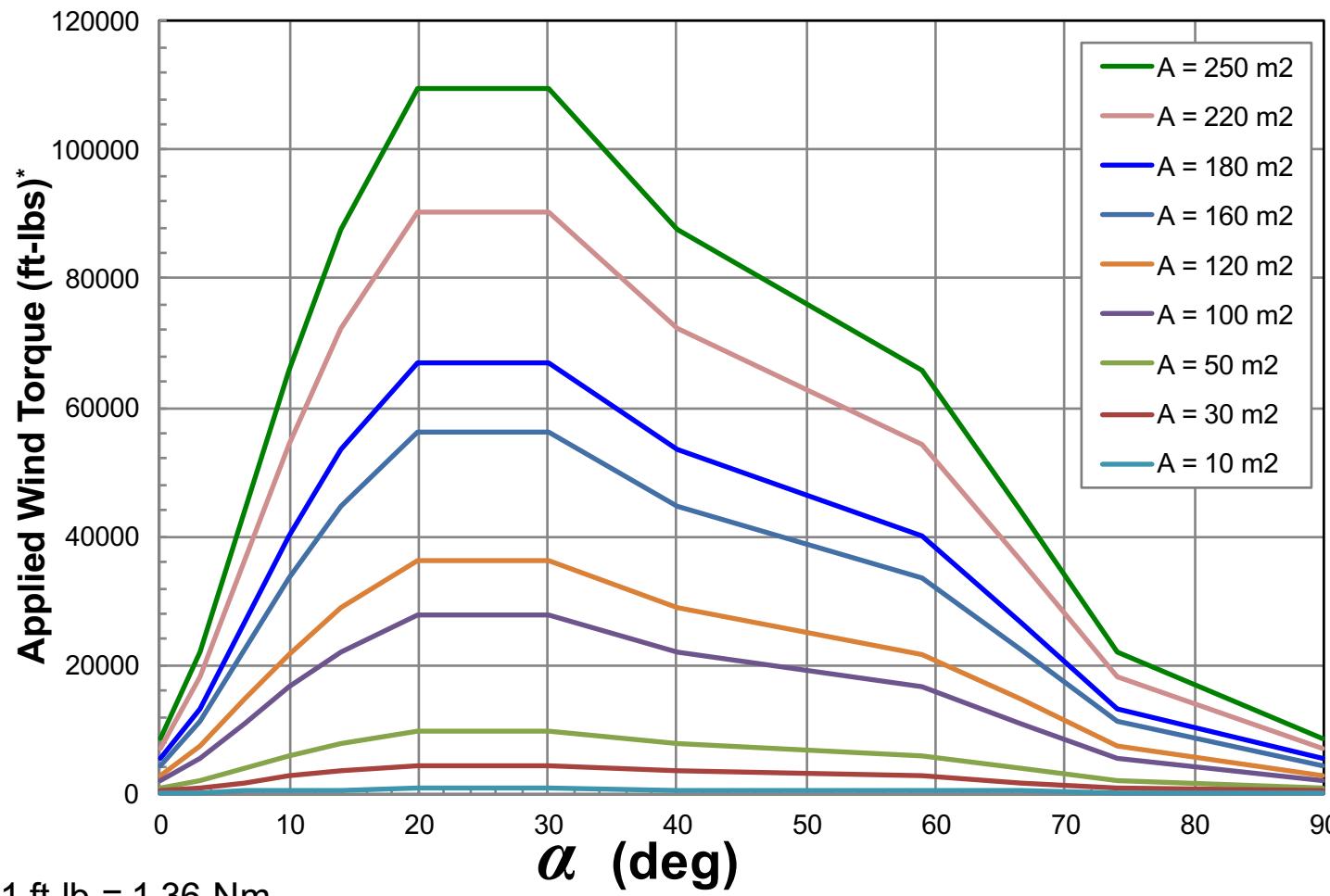
Anforderungen:

- Hohe mechanische Auflösung
- Hohe Steifigkeit
- Geringes Spiel
- Geringe Kosten
- Hoher Wirkungsgrad



Aktuatoren - Lastannahmen

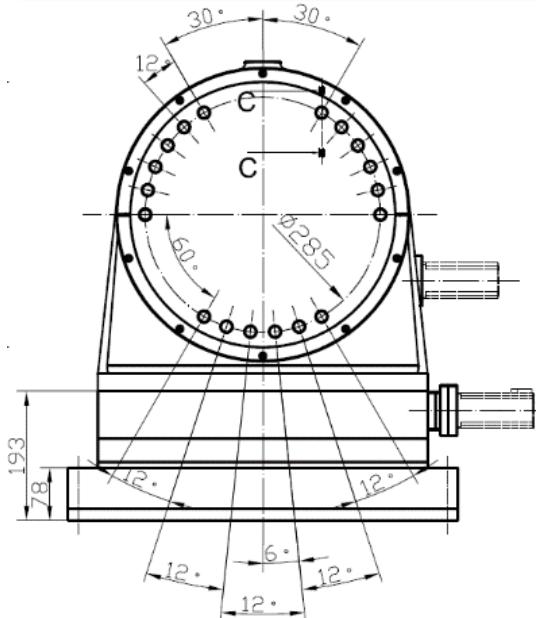
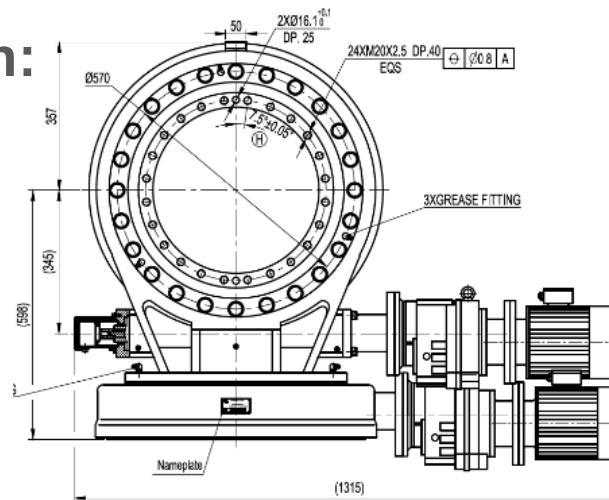
Antriebsmoment durch Windlast vs. Anstellwinkel α



Auswahl des Aktuatorsystems

Possible drive configuration:

Kinematic's KDE21C-125MHA
for ~USD 3500.



→ Prototype needs to have
same drive architecture as
large heliostat!

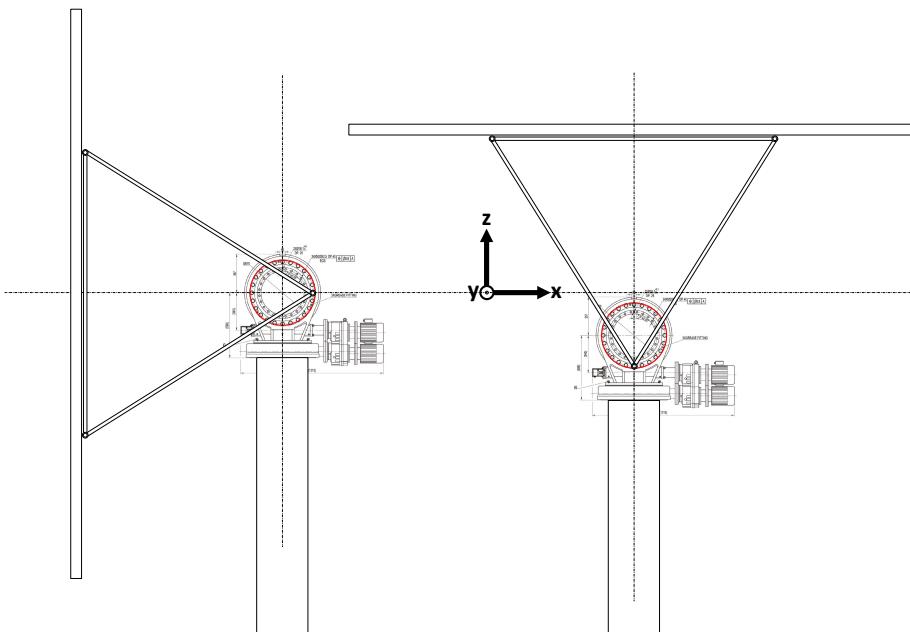


Model *HDR270* by *Zhejiang Hengfengtai Reducer* for ~ USD 2900

Krafteinleitung der Aktuatoren

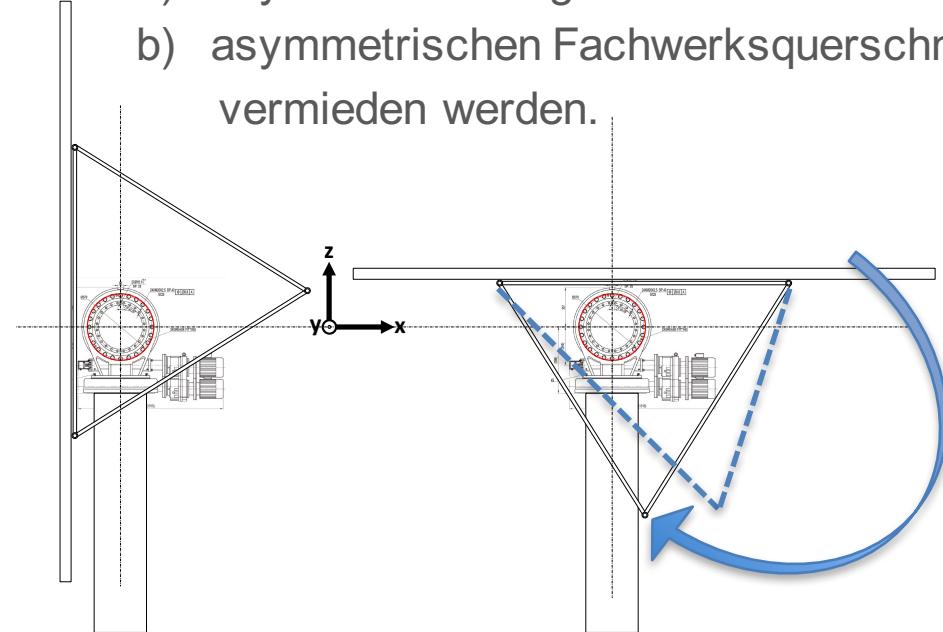
- **Drehpunkt im hinteren Querträger des Fachwerks:**

- Keine Kompakte Bauweise
- Hohes statisches Moment durch Gravitationskraft

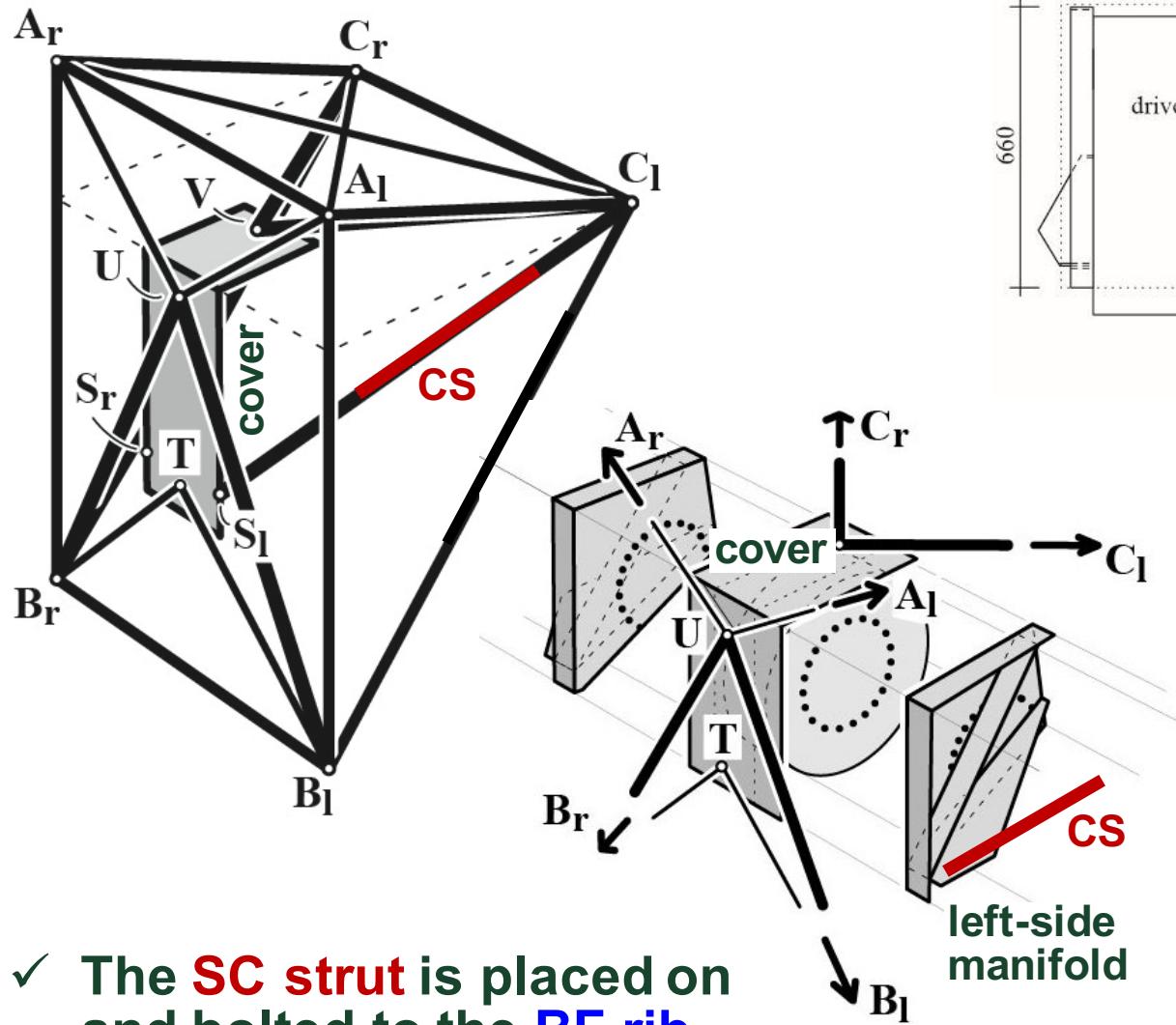


- **Drehpunkt im Inneren des Fachwerks:**

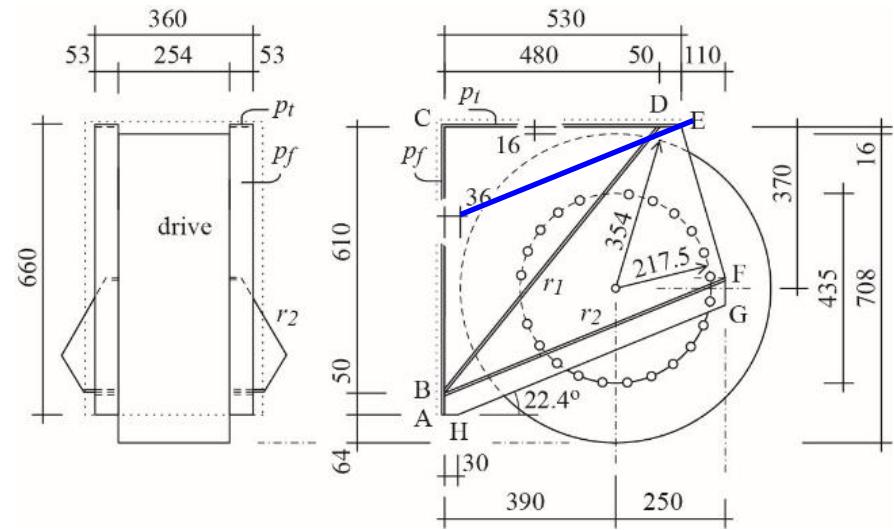
- Kompakte Bauweise
- Geringes statisches Moment durch Gravitationskraft
- Kollision des hinteren Querträgers kann durch:
 - a) asymmetrisch angeordnete Achse
 - b) asymmetrischen Fachwerksquerschnitt vermieden werden.



„Central Hub“

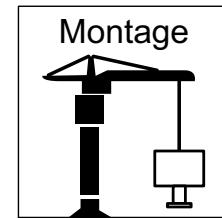


- ✓ The **SC strut** is placed on and bolted to the **BF rib**

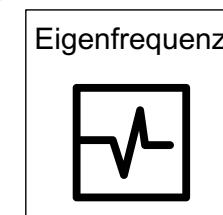
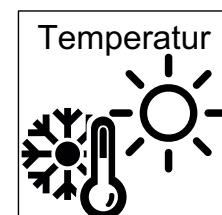
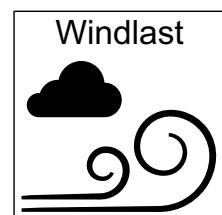
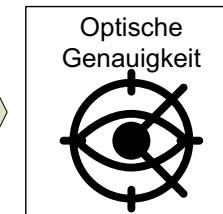


- Cover and sides, attached, make the hub a stiff box
- All constructed of plates, welded (or bolted if angles are used)
- Parts are detailed to allow multiple bolts to the drive face

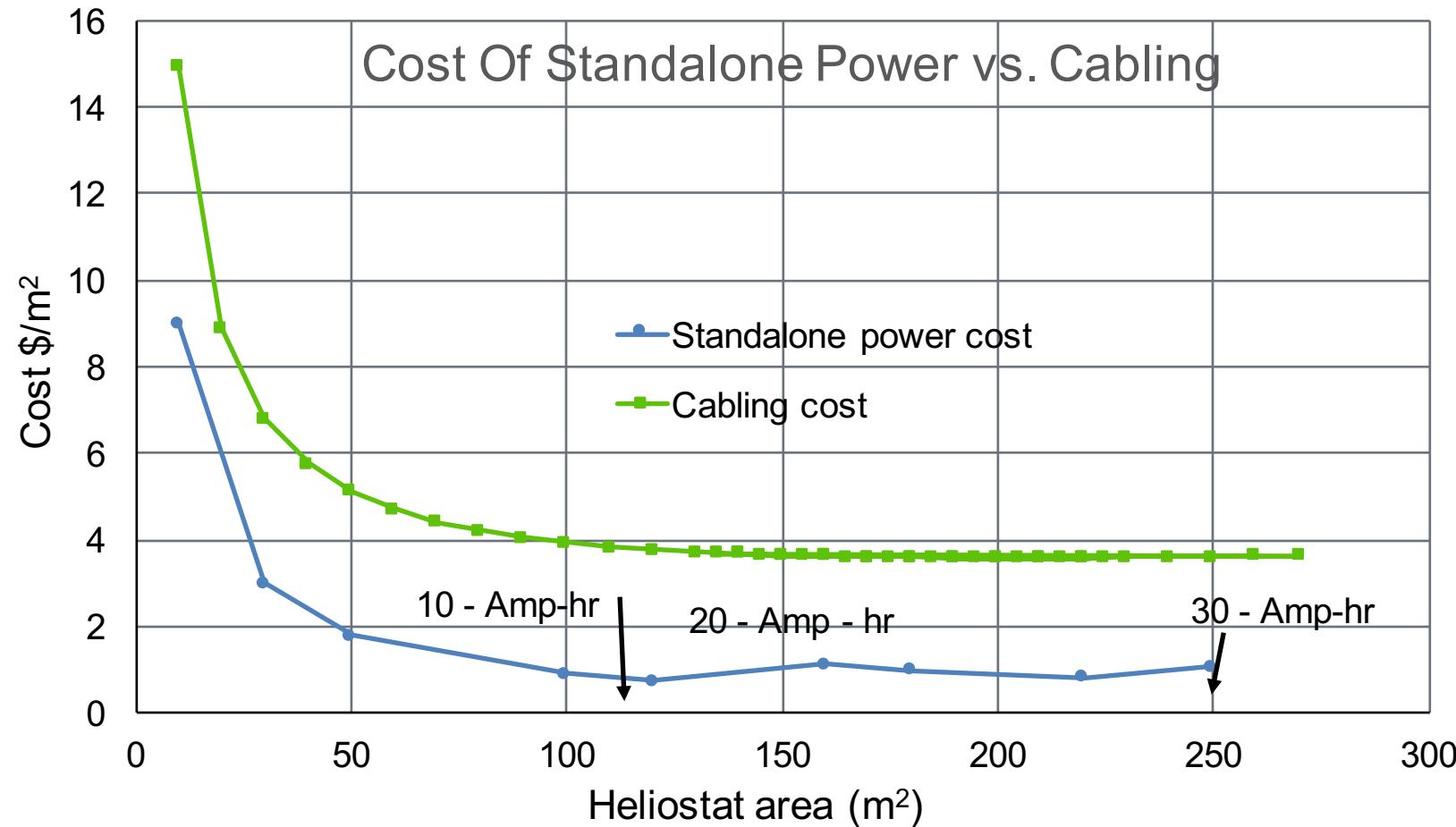
Einige praktische Aspekte – Assemblierung



Heliostatdesign

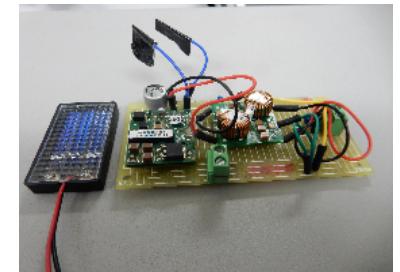
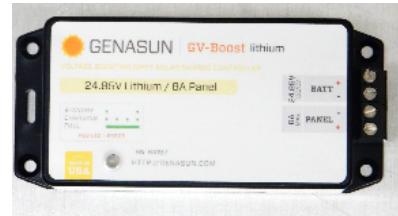


Stand Alone Power System

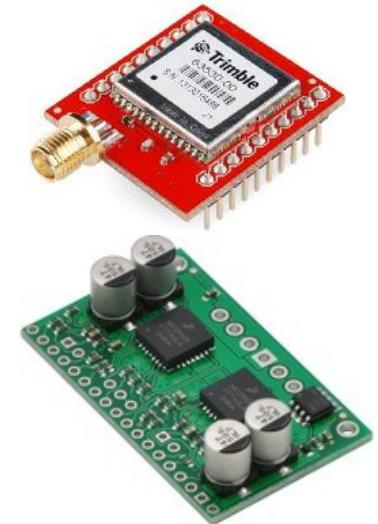
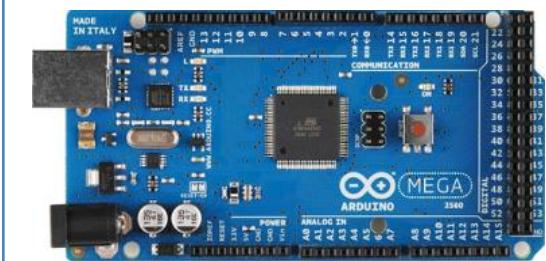
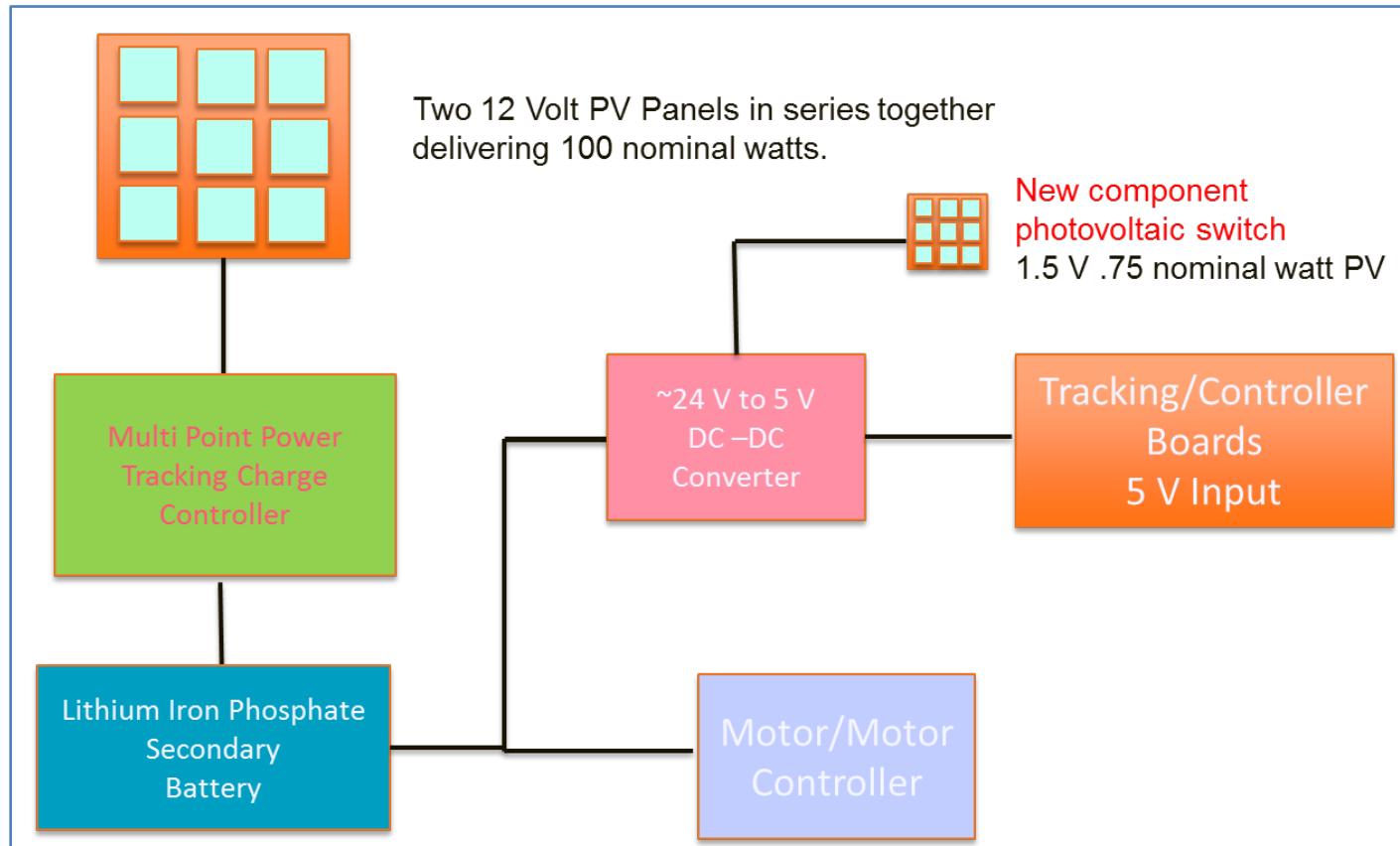


- Standalone heliostat design particularly in the 100 square meter reflective surface area size will provide significant cost savings leading to the \$75/square meter goal

Stand-Alone Power System



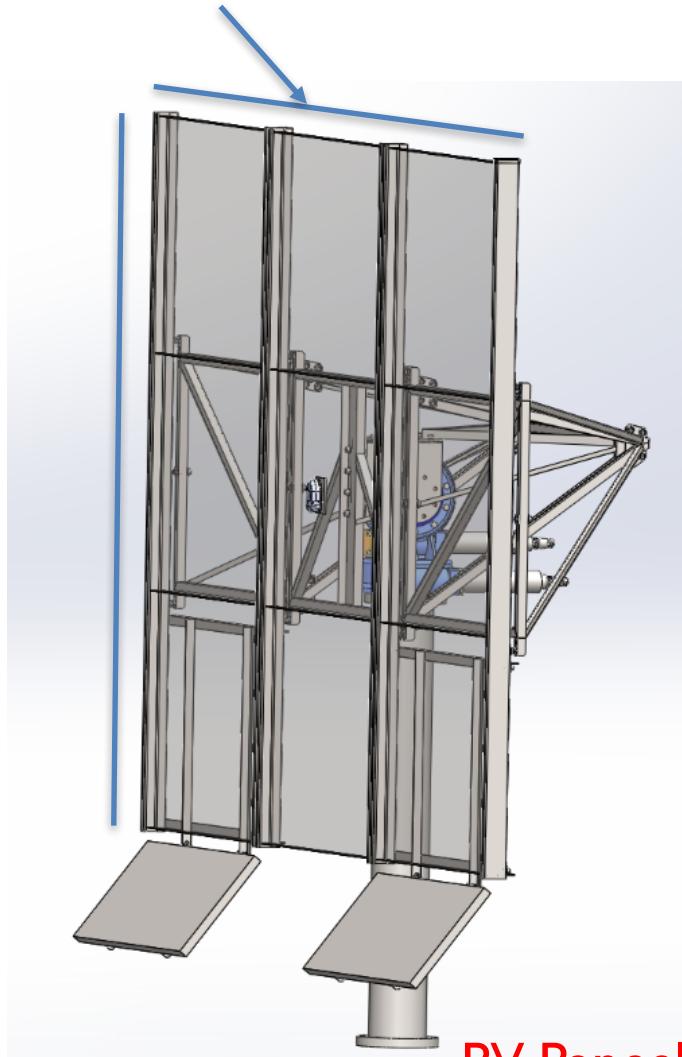
PSP05-DC24-5



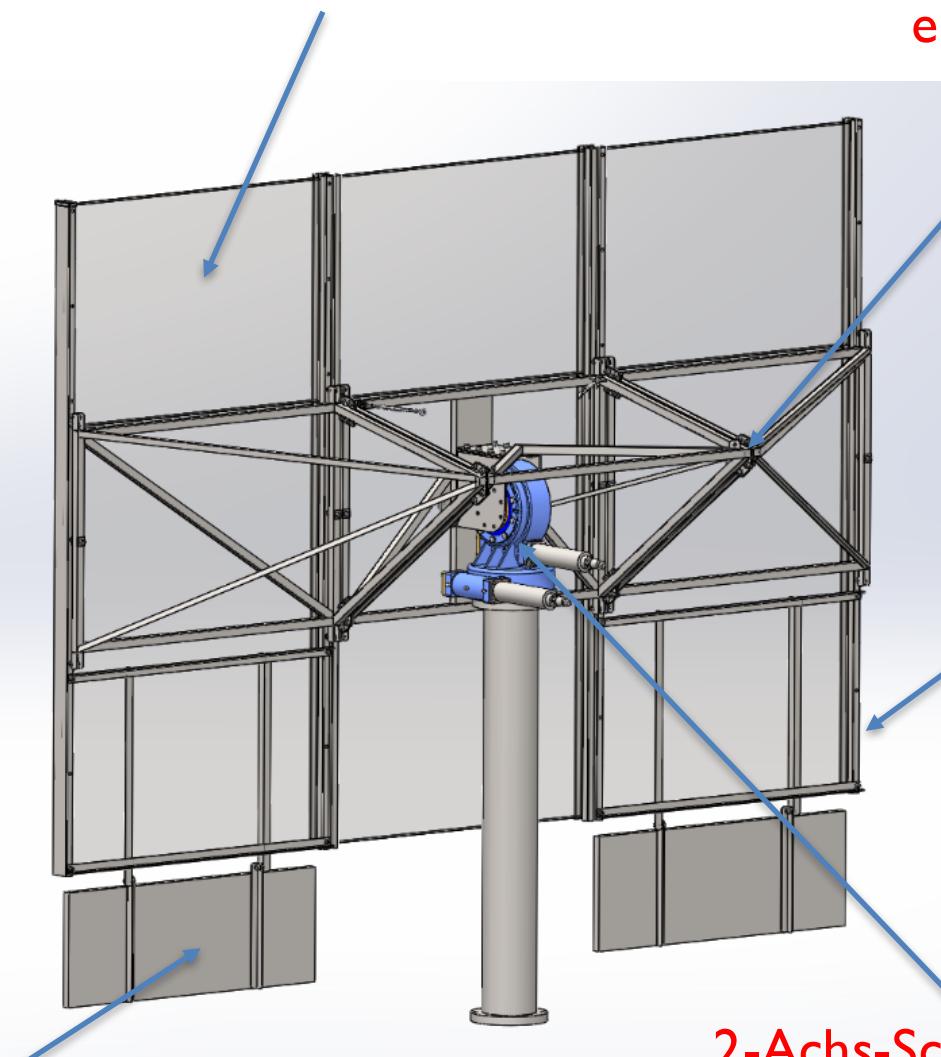
23

Small Scale Prototyp

Fläche: 3x2 m



9 Spiegel: je 0.667x1m und 1.25" stark



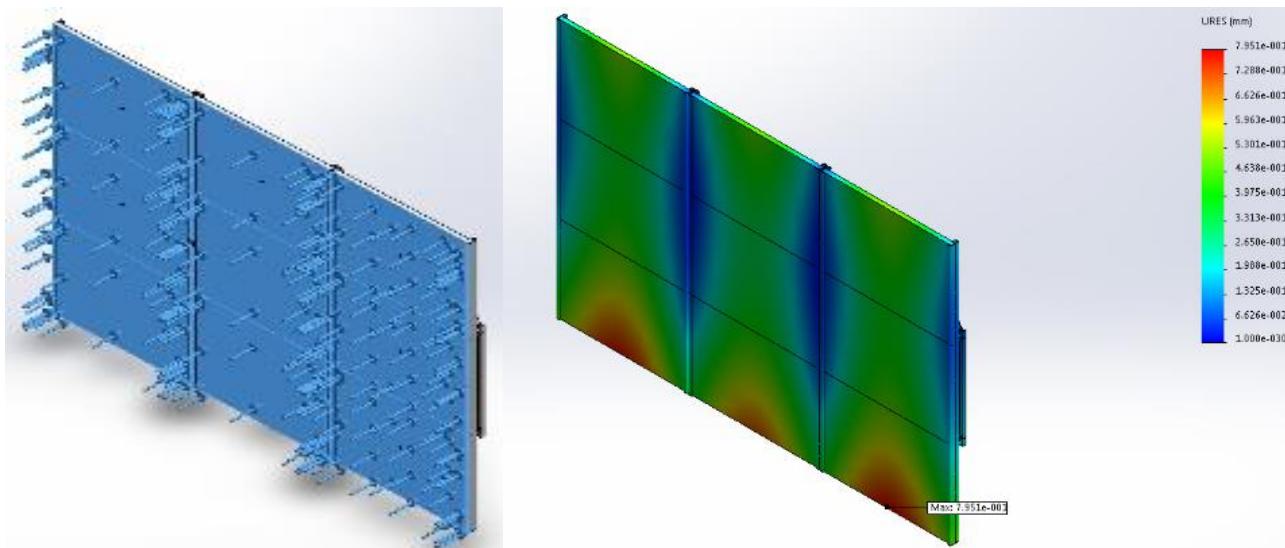
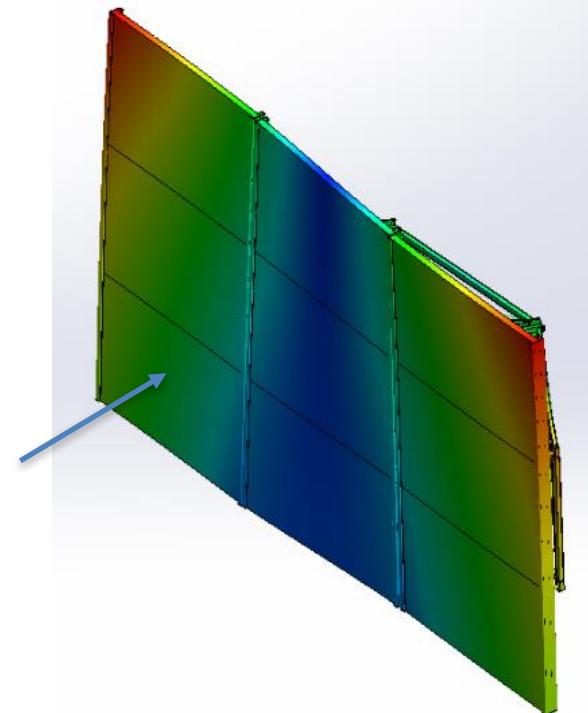
3 Fachwerkelemente

C-Schienen

2-Achs-Schwenktrieb

Ergebnisse der FE-Rechnung

- Maximale Durchbiegung:
 - ✓ 0.6mm (COMSOL)
 - ✓ 0.8mm (SOLIDWORKS)
 - ✓ 1.1mm (ANSYS)
- Erste Eigenfrequenzen im Bereich 17-20 Hz

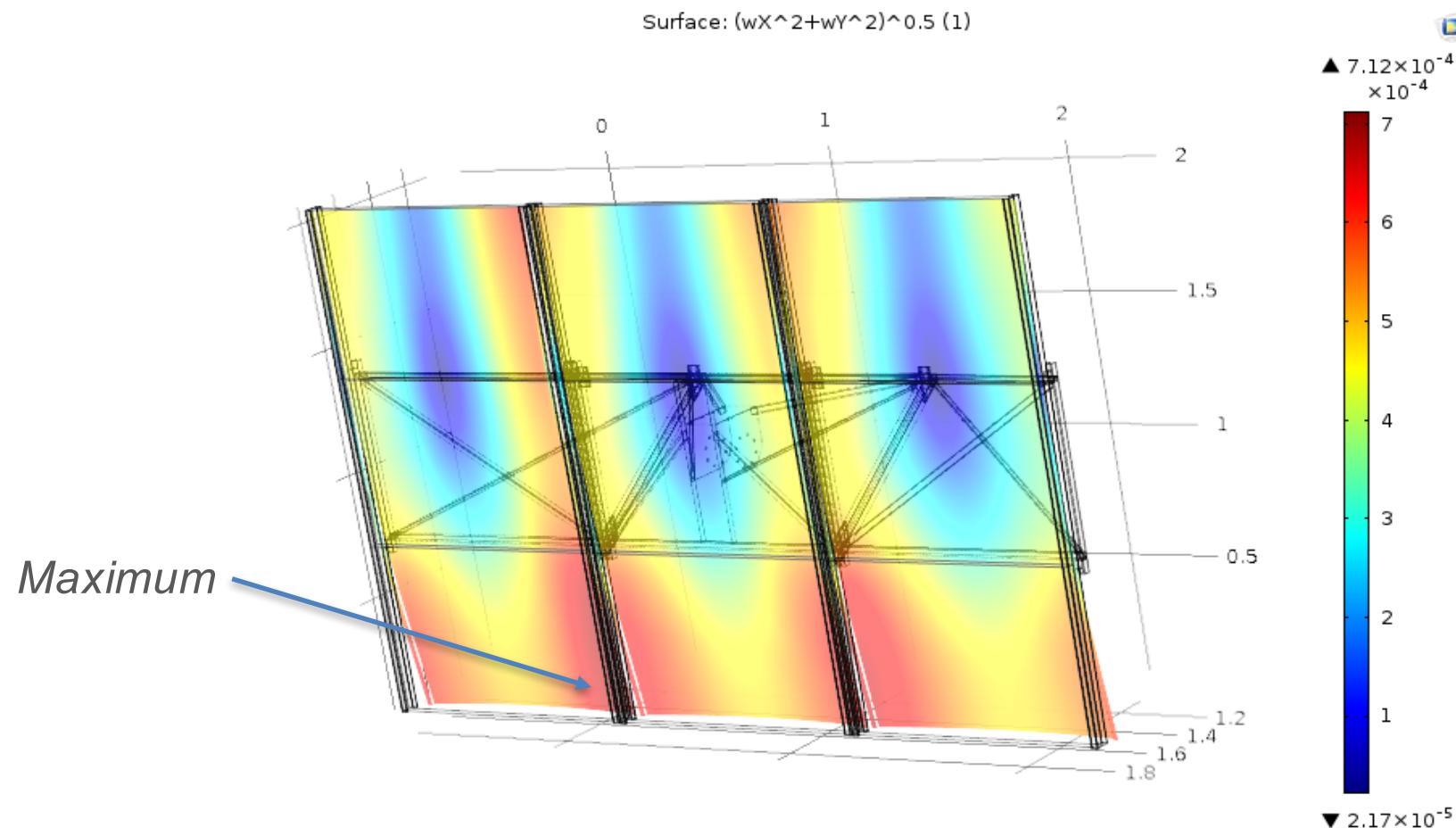


Uniform pressure load of 300 pa and corresponding displacement (0.795 mm max.) of the heliostat in **SOLIDWORKS**.

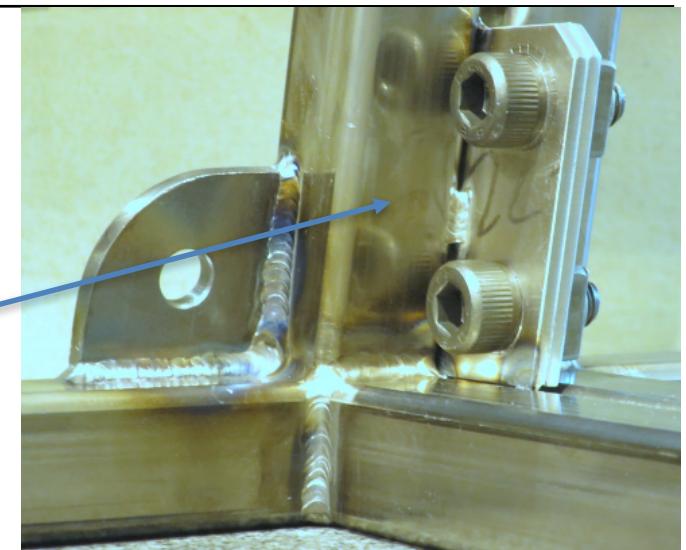
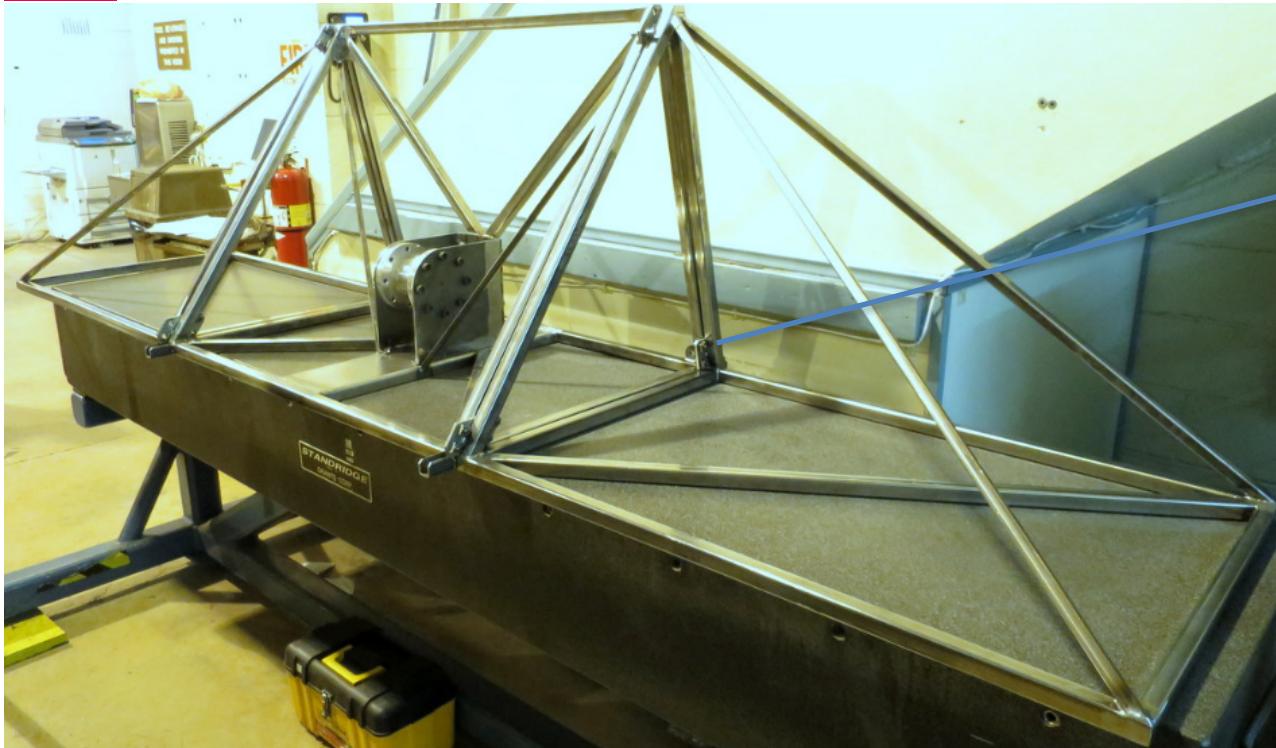
Ergebnisse der FE-Rechnung

RMS Winkelfehler bei 35 mph Wind:

- Maximum ca. 0.71 mrad nahe dem unteren Ende der C-schienen.
- Durchschnittlicher RMS-Winkelfehler: 0.4 mrad!

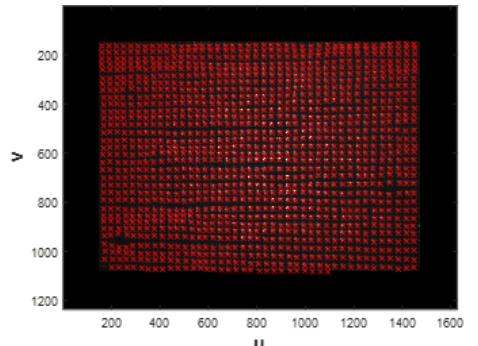


Fertigung des Prototyps

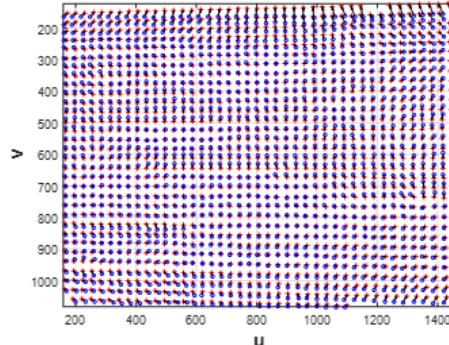


Fotogrammetrie: Reverse Shack-Hartmann Test

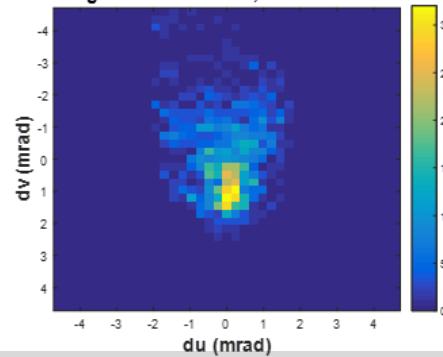
Facet 00



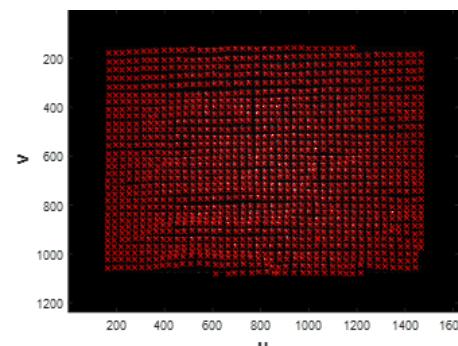
Spot Centroids (o) vs Homography Predictions (+)



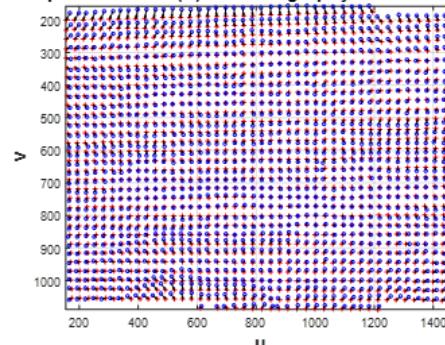
Histogram of Residuals, RMS: 0.693 mrad



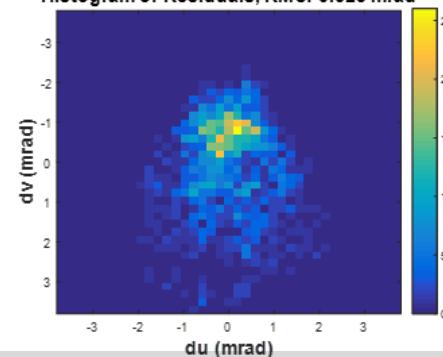
Facet 01



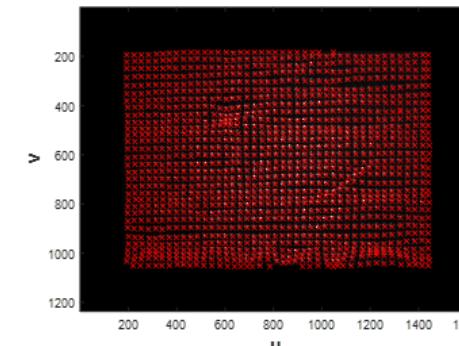
Spot Centroids (o) vs Homography Predictions (+)



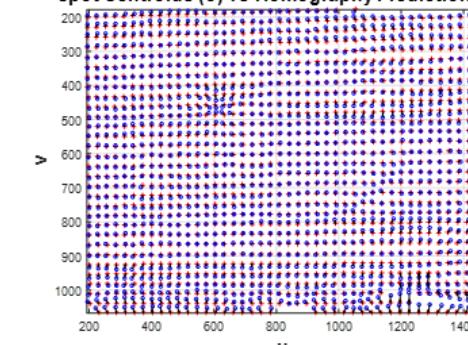
Histogram of Residuals, RMS: 0.625 mrad



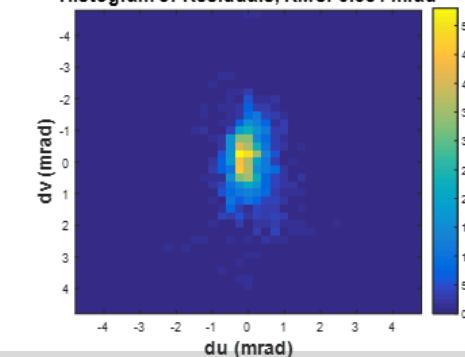
Facet 02



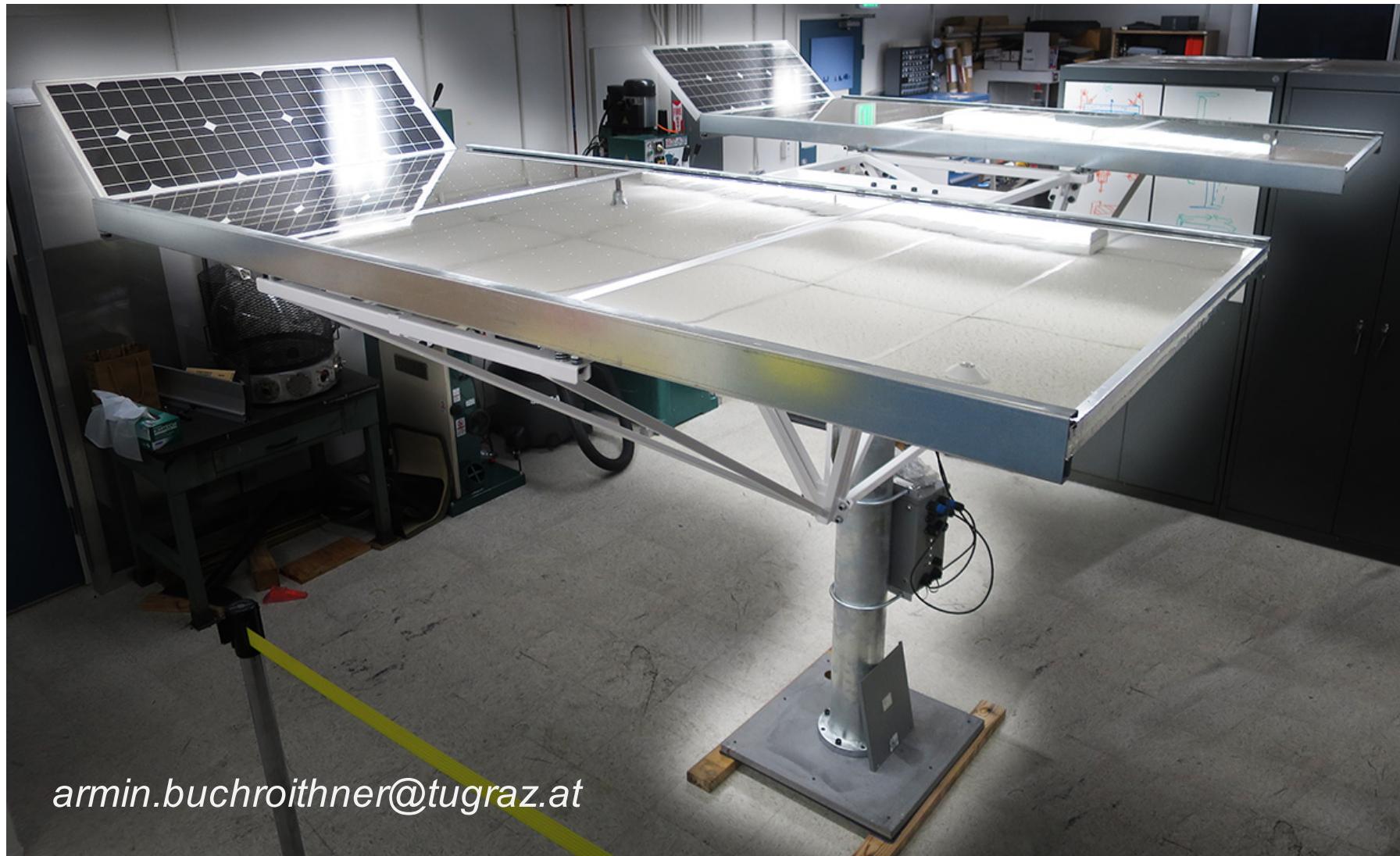
Spot Centroids (o) vs Homography Predictions (+)



Histogram of Residuals, RMS: 0.581 mrad



Danke für Ihre Aufmerksamkeit!

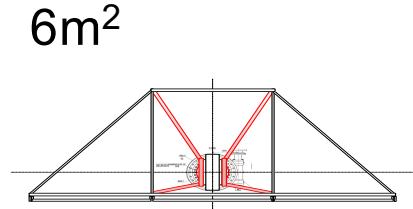
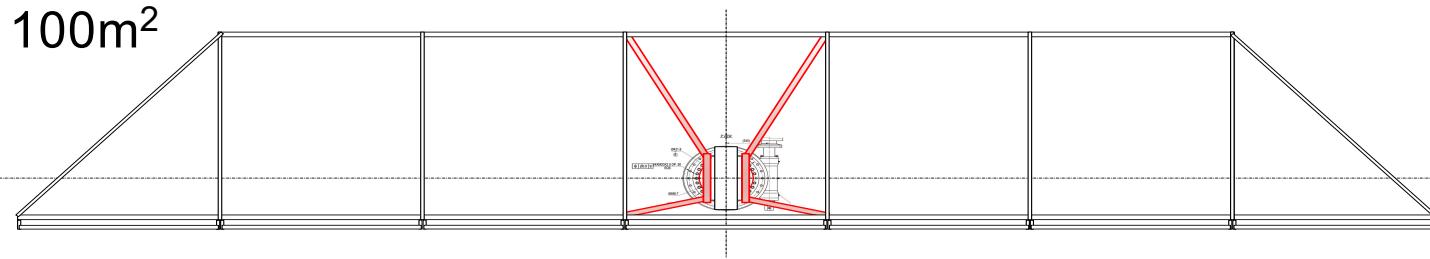
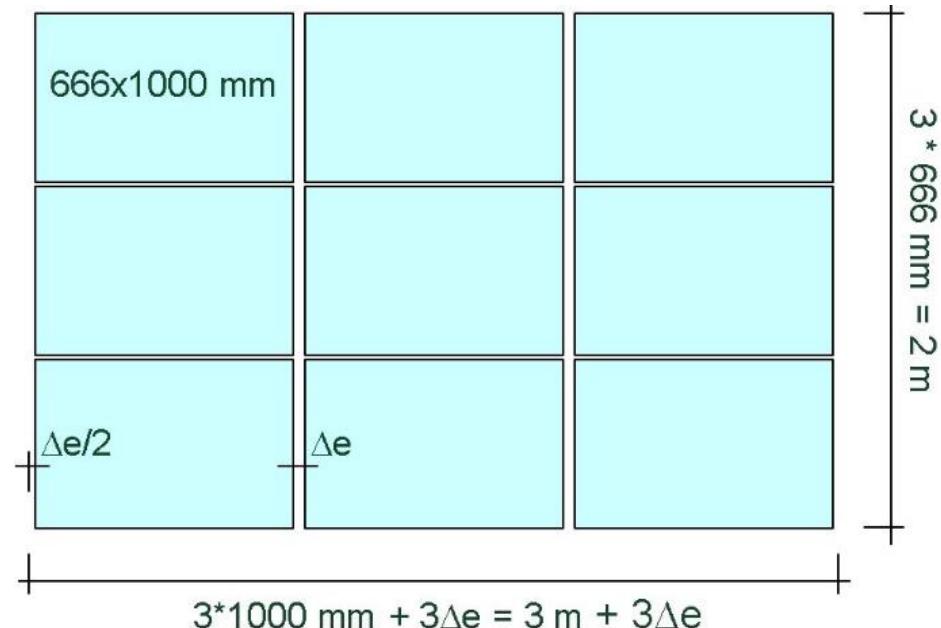


6. Prototyp

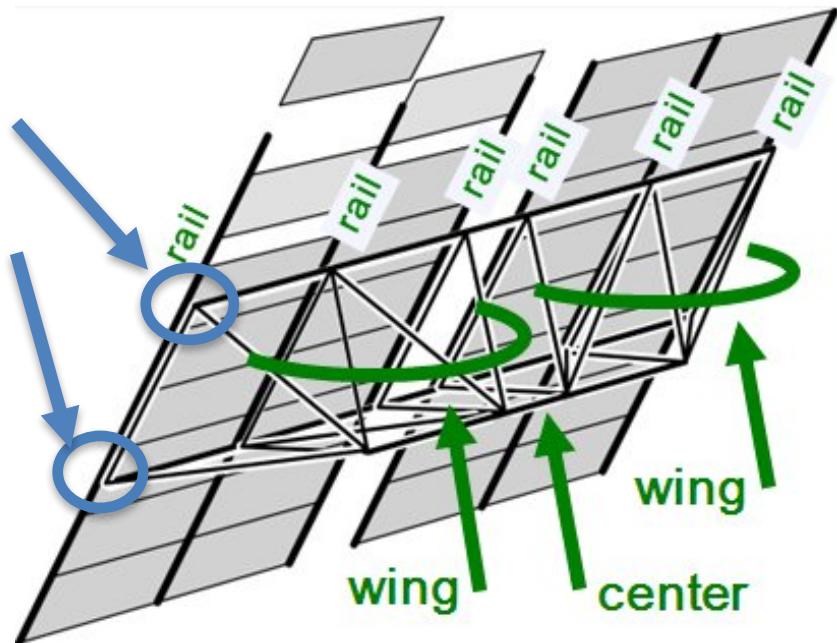
Skaliertes Modell:

Aspect ratio: 3x2m instead of 2x2m:

- General prototype architecture must have more than 2 “bays” for representative truss design!
- Torque requirements for drives are scaled using *Peterka’s* approach.
- Manufacturing constraints regarding EPS foam core.
- Deflection under wind load and optical error expected to be slightly smaller.



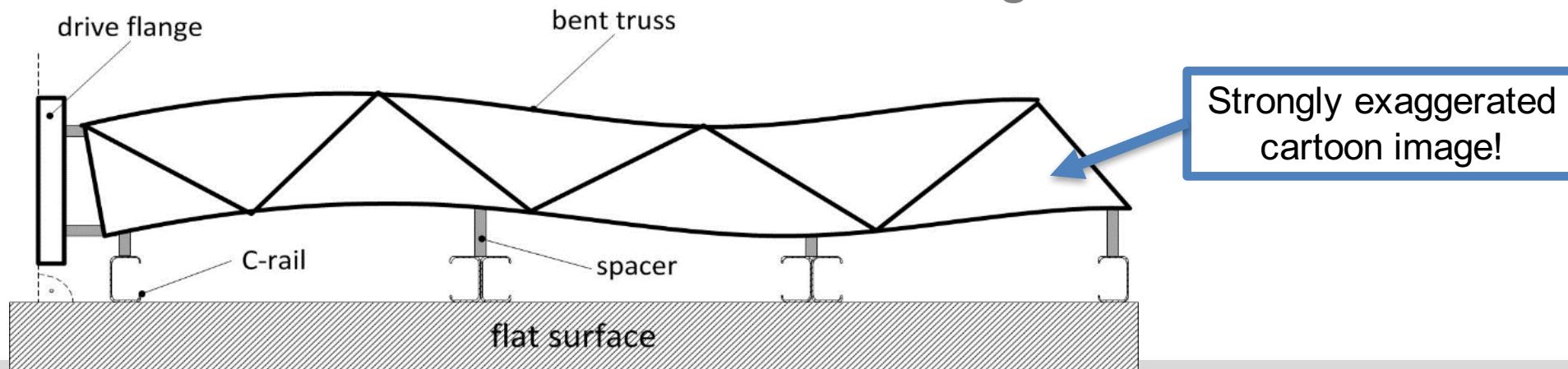
Prototype Design



Truss-C-rail interface

Rail design as in Phase I:

- ✓ Easy assembly and replacement of facets.
 - ✓ Edge protection of sandwich facets.
 - ✓ High area moment of inertia of rails and hence low deflection.
- ! Issue of welding distortion.
- ! Facets (inner edges of c-rails) need to be aligned.



Prototype Design

For 6m²: Higher flexibility, interchangeable parts, possible adjustments.

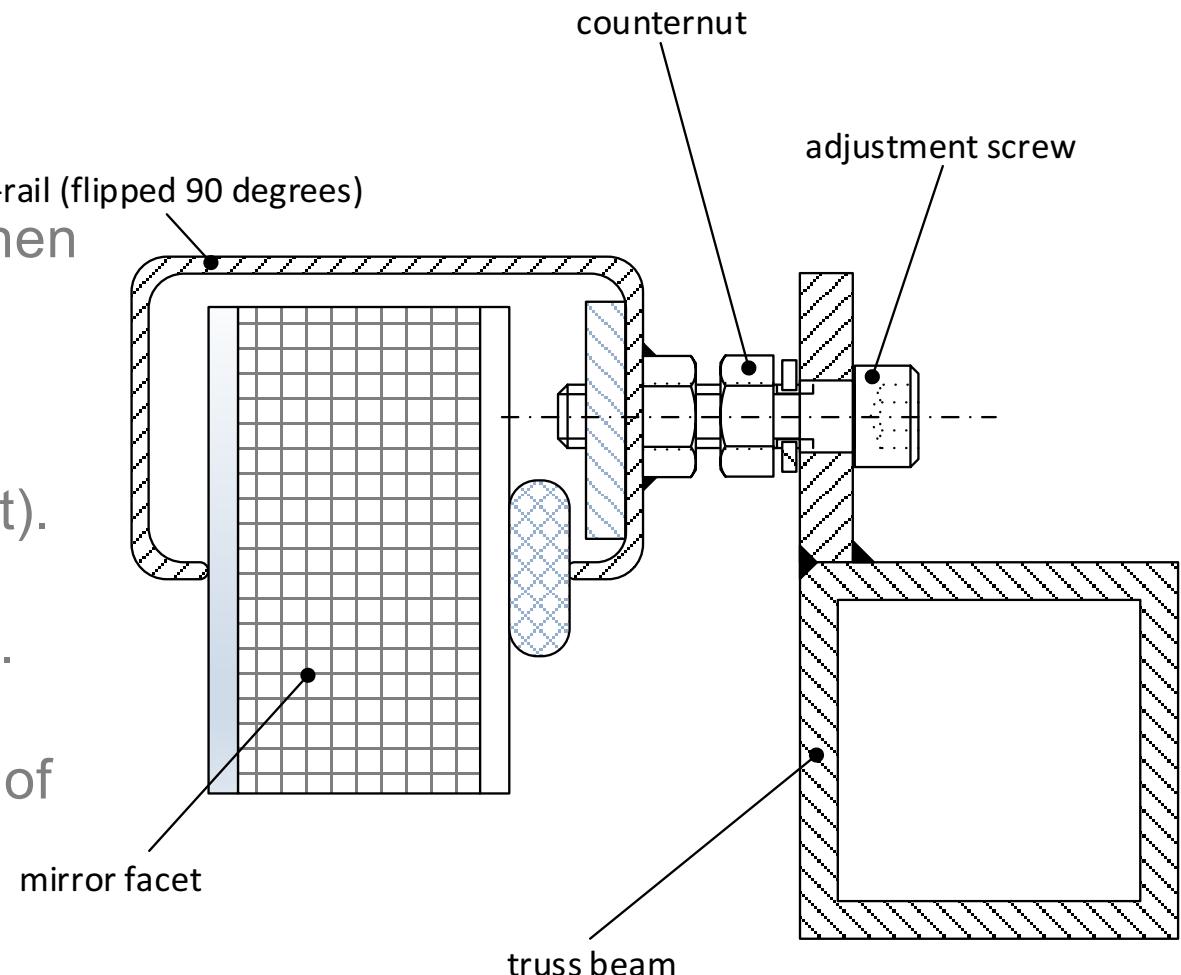
Adjustment screws:

Advantages:

- ✓ Very easy do adjust, even when completely assembled.
- ✓ C-rails can be interchanged.

Disadvantages:

- Play in thread (→ counter nut).
- No direct contact between longeron and c-rail (stability).
- Flaps need to be welded.
- Favors square cross section of truss longeron.
- Welding nut to c-rail.

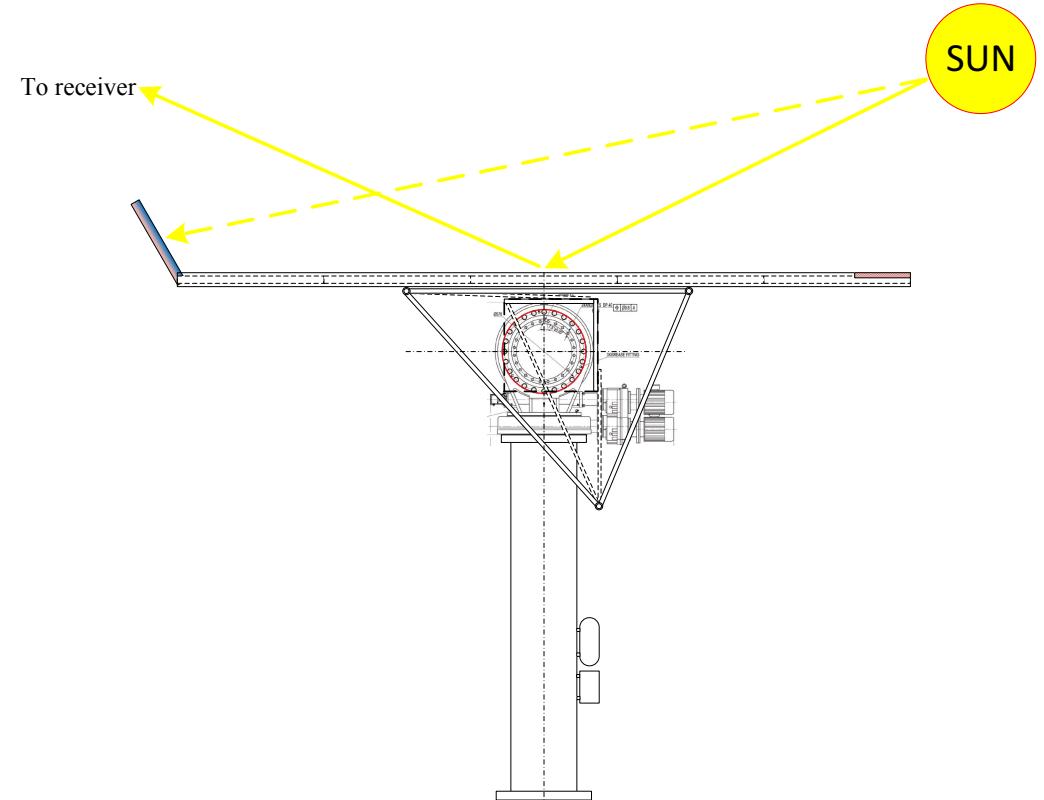
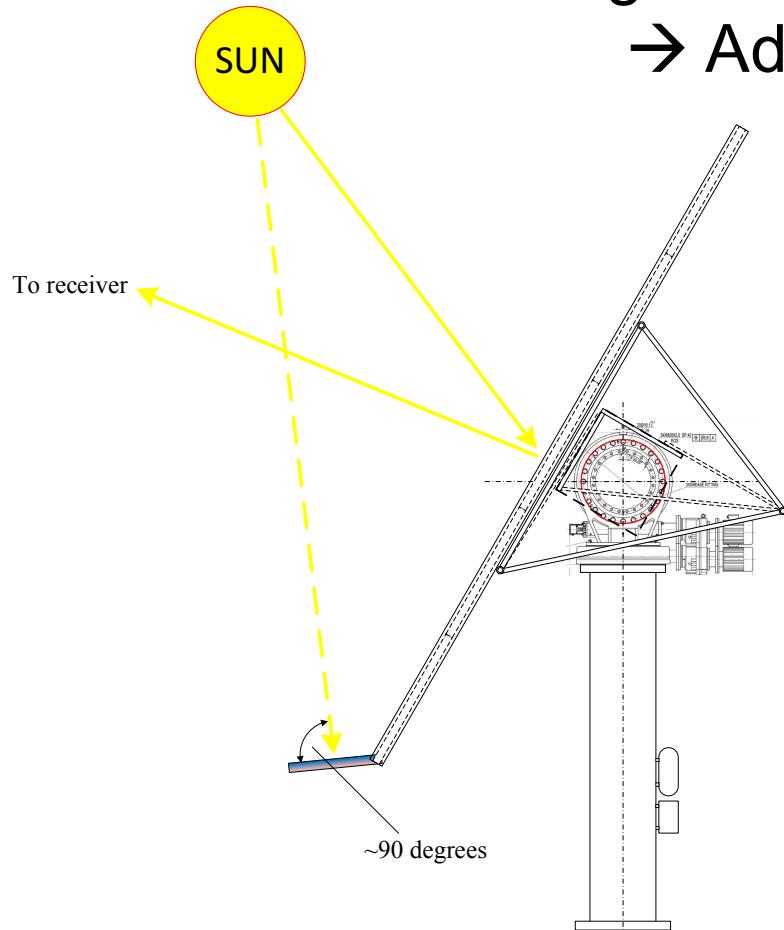


PV Mounts

Motion of heliostat different from PV tracker

Angle of PV vs. angle of mirror facet:

→ Adjustable hinge to investigate influence



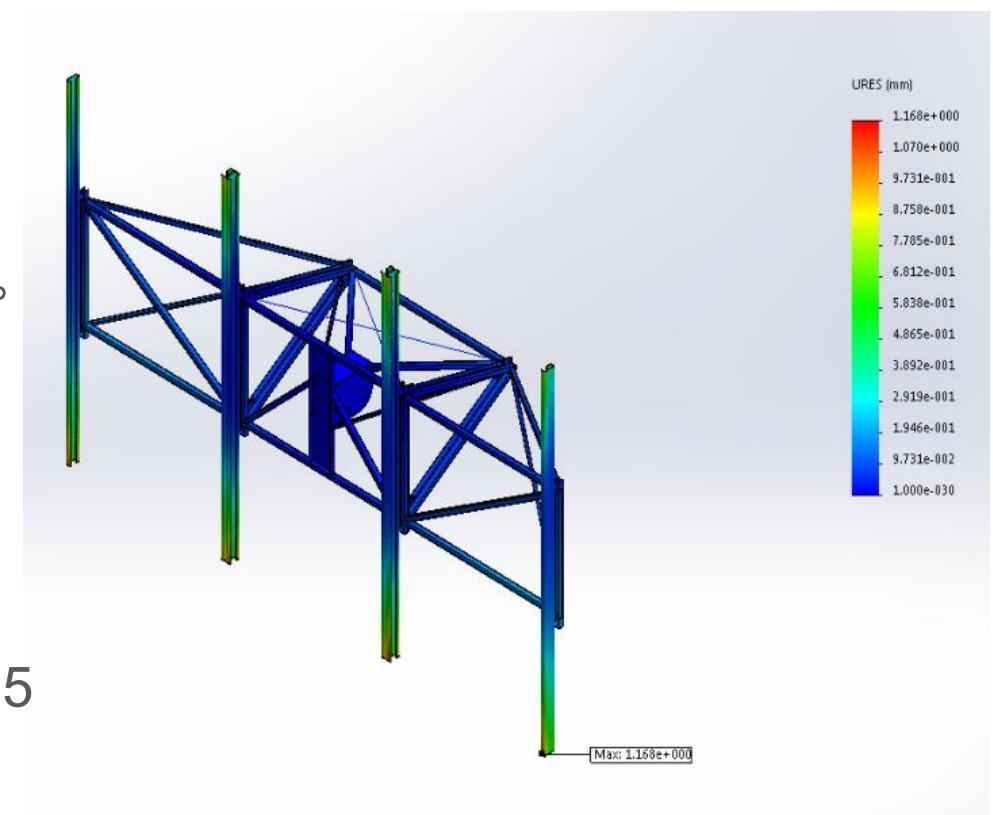
(PV mounted at bottom to minimize shadowing)

Finite Element Analysis of Prototype

- Model was cleaned up and simplified for meshing
- FEA din *SOLIDWORKS*, *ANSYS* and *COMSOL Multiphysics*

Load cases investigated:

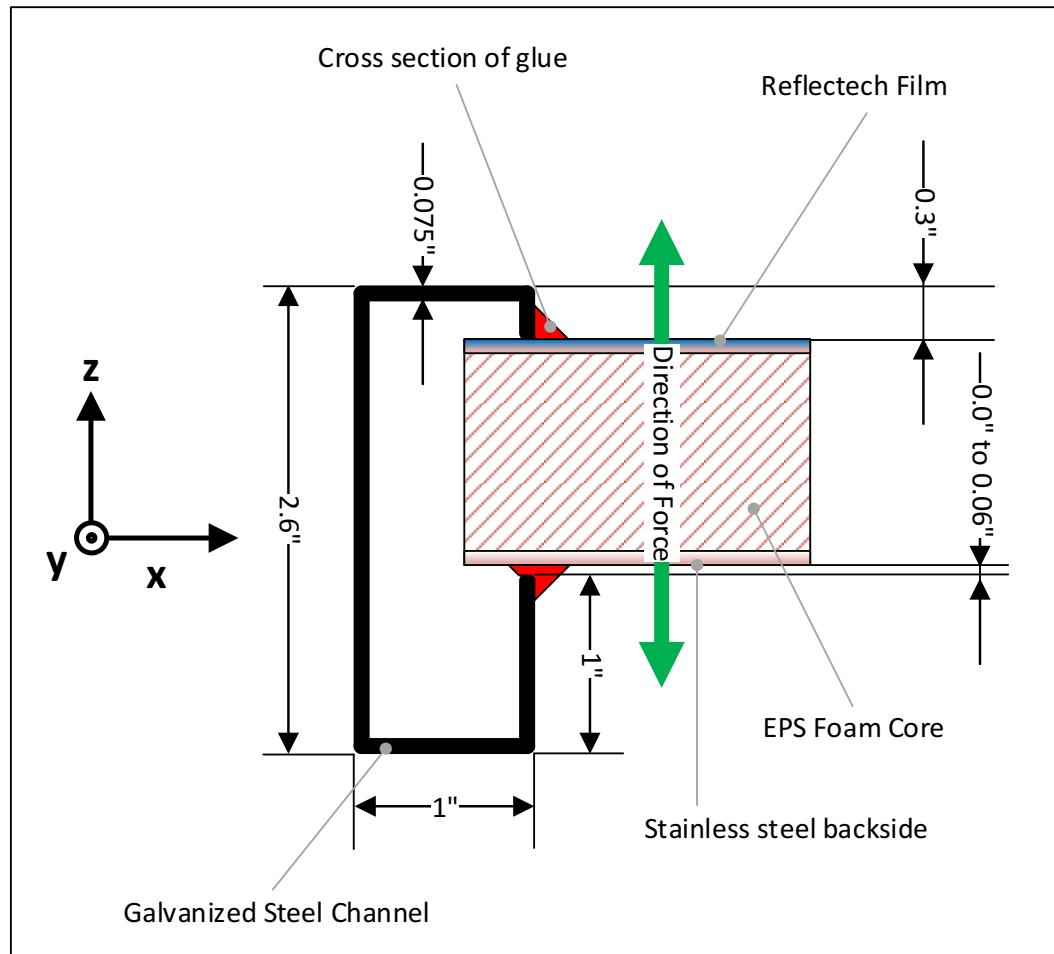
- 1) Deflection and stress under
- 2) 35mph winds at 0° , 45° and 90° elevation angle
- 3) Dynamic response and eigenfrequency
- 4) Impact of PV panel on deflection
- 5) Stress during stowed condition (85 mph)



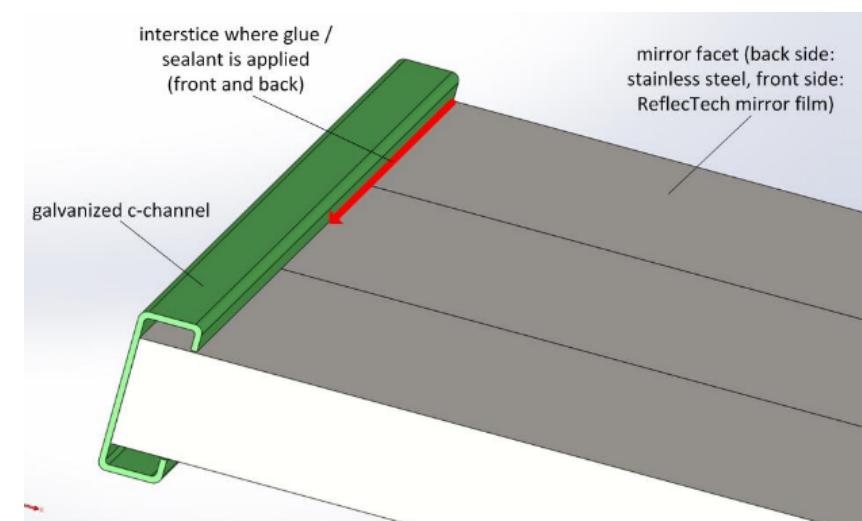
Lessons learned from the prototype will influence large scale design!

C-rail facet interface

First solution worked out in cooperation with **Sika USA**



- Uniform pressure load of only 300 pa on facets.
- Each facet spans 1m across (x direction) and is 0.667 m long in y direction.
→ This means a force of 200N has to be supported by the glue / rail contact.
- The force will be distributed over the 4 beads.
→ Line load of ~1.5 N/cm

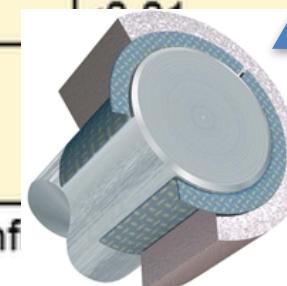


Auswahl des Aktuatorsystems

Übersicht der Antriebsoptionen

Option	Azimuth	Elevation	Capability	Pointing Accuracy (Azimuth) (degrees)	Pointing accuracy (Elevation) (degrees)	Stow time (min)	Total Cost/m ²
Design 1	Dual Axis		360 deg on azimuth and 90 on elevation	<0.01	<0.01	5	~ 40
Design 2	2 linear actuators	1 linear actuator	360 deg on azimuth and 90 on elevation	<0.01	<0.01	1 - 8	~ 42
Design 3	Slew drive	1 linear actuator	360 deg on azimuth and 90 on elevation	<0.01	<0.01	1 - 8	~ 34
Design 4	bicycle chain/rotary	2 linear actuators	180 deg on azimuth and 180 deg on elevation	TBD *	0.01	5	TBD
Design 5	bicycle chain/rotary	bicycle chain/rotary	180 deg on azimuth and 180 deg on elevation	TBD *	0.01	5	TBD

* Design numbers not finalized as unique design depends on final configuration
 significant advantage due to "deep structure"



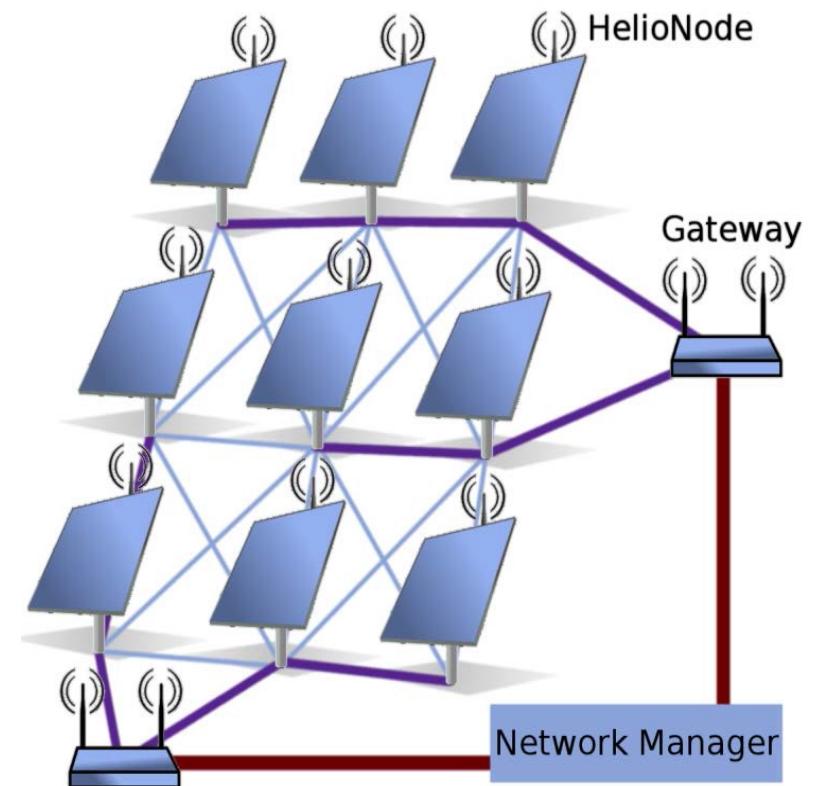
ever expect

Image: Saint-Gobain

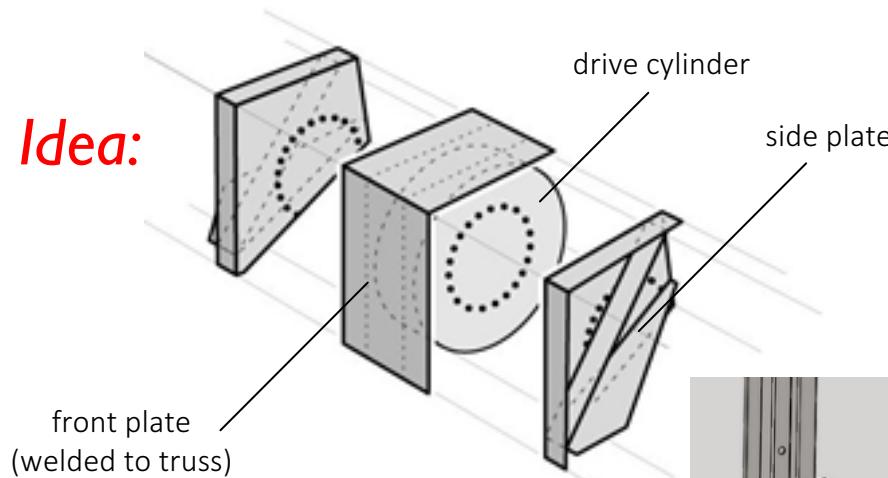
5. Control System

Aufgabe des Heliostat Control Systems:

- Bestimmung von Azimut und Elevation angle basierend auf
 - ✓ Datum und Tageszeit
 - ✓ Position des Heliostaten
 - ✓ Position des Receivers
- Stowe commands
- De-focusing für Anlagenwartung



Truss and drive interface

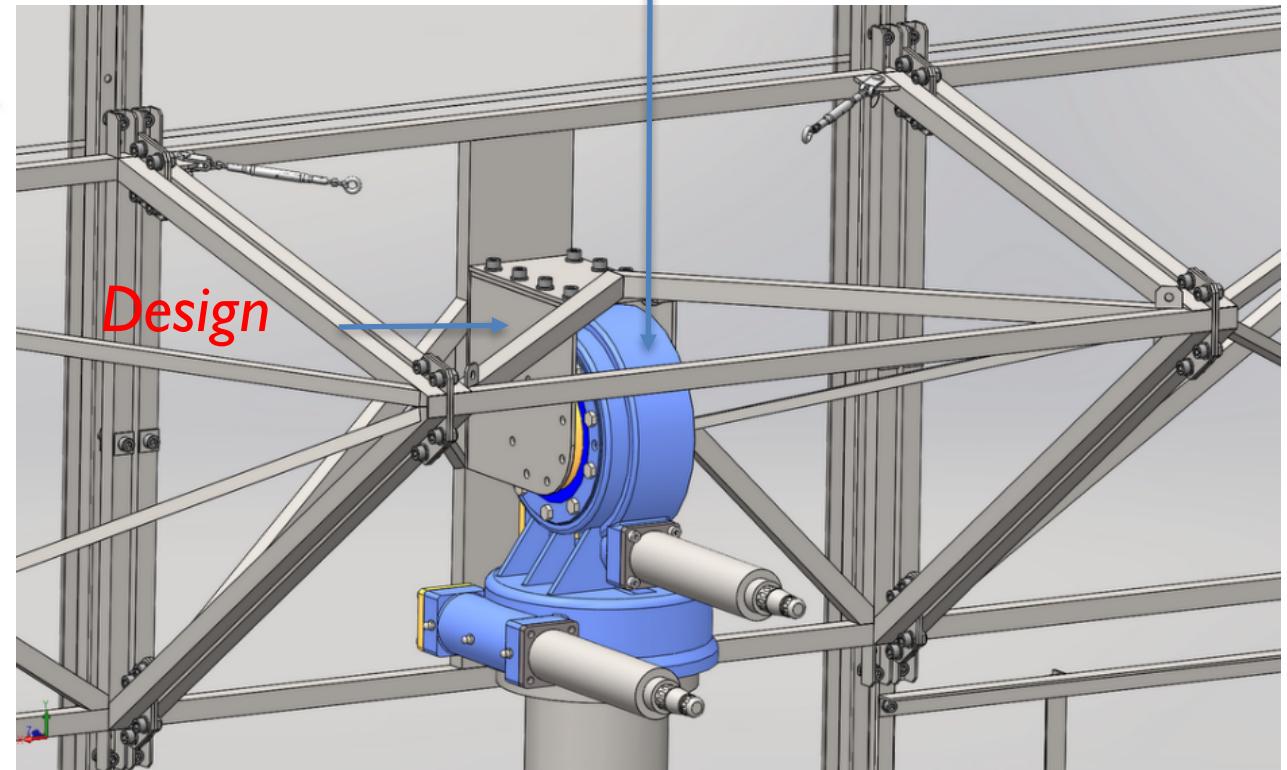


KDE7-E by Kinematics

- output torque 1300 Nm
- tilting torque 6780 Nm

Bolted center box:

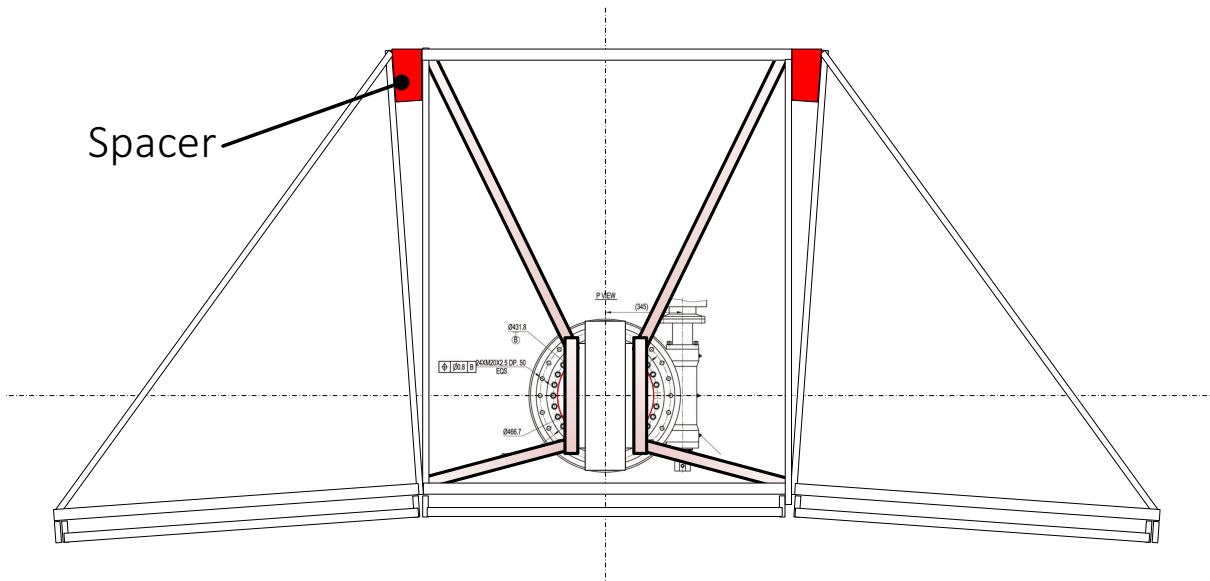
- Compensate welding distortion
- Avoid tight tolerances
- Easy assembly



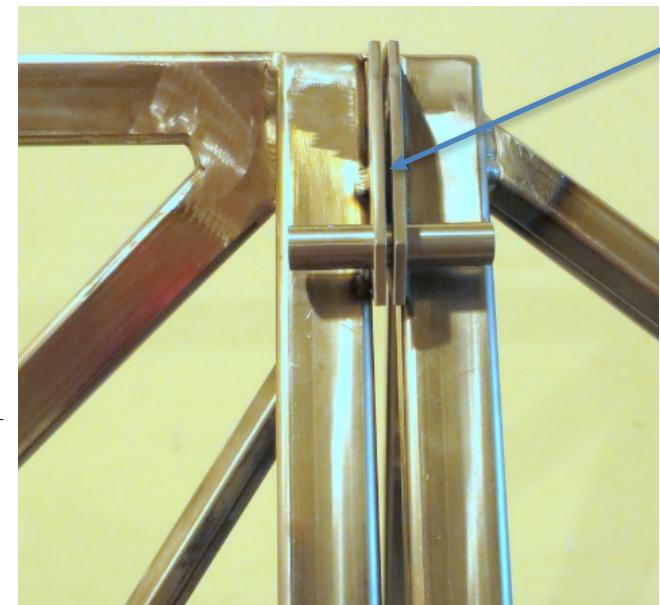
Manufacturing of truss elements and pylon

- a) Flatness of the entire truss assembly
→ To be compensated with canting option
- a) Flatness of the c-rails
→ To be compensated with c-rail adjustment option

a) canting option



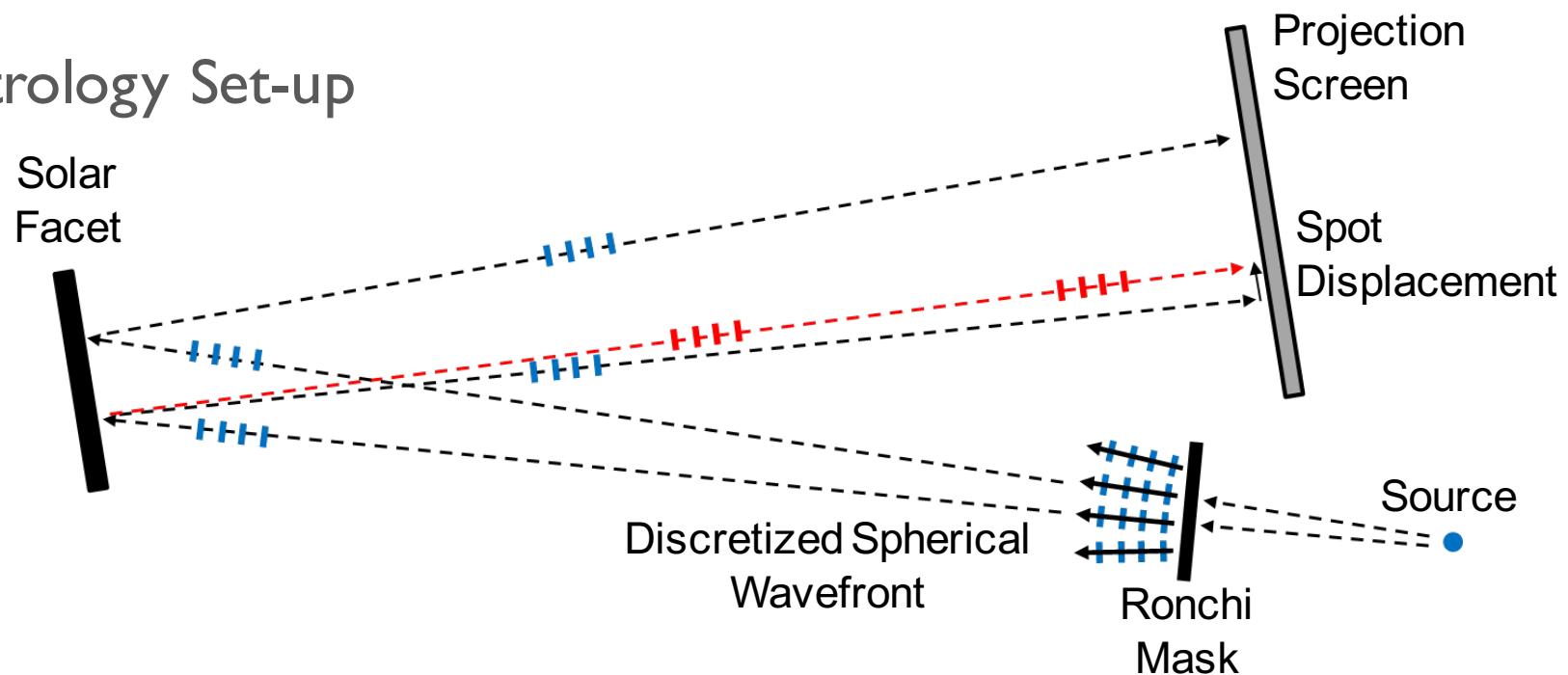
Principle of canting (top view).



Gap between central truss and side pyramid where spacer is place.

Photogrammetrische Charakterisierung

Metrology Set-up



■ Reverse Hartmann Test:

- Discretized spherical wavefront produced via Ronchi Mask
- Spot pattern produced on projection screen (does not require formation of an image)
- Comparison of distorted pattern to nominal grid allows for deduction of surface slope errors

Status: Prototype Assembly

- ✓ Assembly of mechanical modules completed!

