Solar tracking in Console

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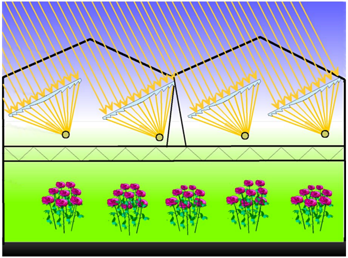
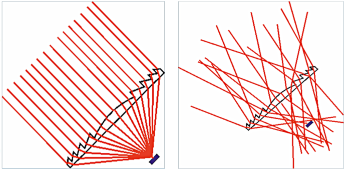
Outline

Console: Concentrated Solar Energy

- Use a lens to concentrate direct sunlight on an efficient solar cell
- Diffuse light remains for ambient lighting
- Applications: greenhouses, glass roofs, shopping centres, *etc.*
- Issue: must track the Sun!





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A solar-tracking routine

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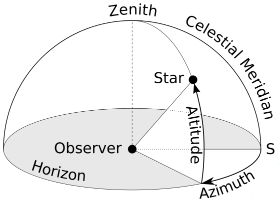
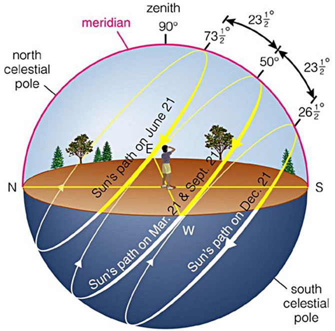
Requirements:

- Accurate ($\lesssim 0.01^\circ$)
- Fast (for microcontroller, cheap hardware)
- For every location on Earth
- For each instant (diurnal, annual motion)
- Position in azimuthal and parallactic coordinates





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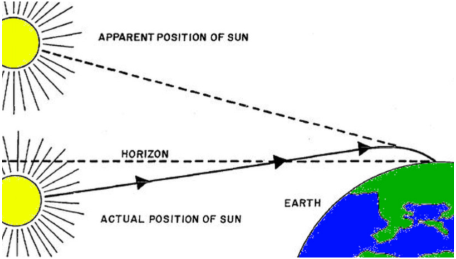
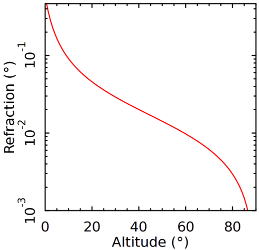
Atmospheric refraction

Refraction in the earth's atmosphere:

- $\sim 0.5^\circ$ at sunrise and sunset
- 0° in the zenith
- Average in the Netherlands: $\sim 0.07^\circ$





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Development and testing

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Developing and testing the SolTrack routine:

- Based on libTheSky; open source
- Correction for atmospheric refraction
- Conversion to horizontal, parallactic and gimbal coordinates: use on *any* tracker
- Rise and set of the Sun
- http://soltrack.sf.net

Testing the routine:

- 100.000 random dates and times:
  - 2017 – 2116
  - Sun above the horizon
  - azimuthal and parallactic coordinates
- Compare to accurate routines for:
  - position: VSOP 87 ($\sim 10^{-6\circ}$)
  - refraction (numerical integration)

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Accuracy of SolTrack

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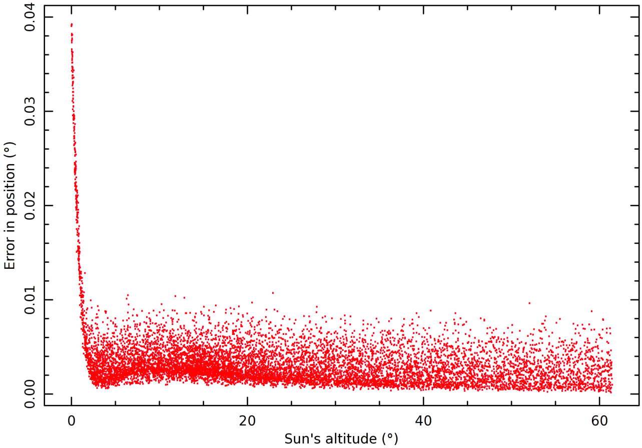
Result:

- Accuracy: $0.0030 \pm 0.0016°$



Van der Sluys et al., in preparation

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Accuracy of SolTrack

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Result:

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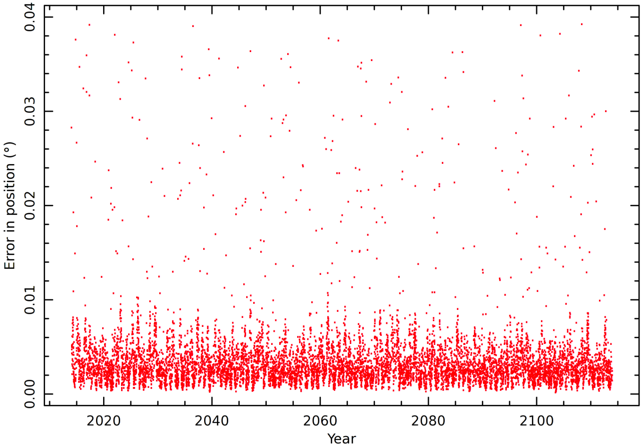

Van der Sluys et al., in preparation

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SolTrack vs. SunPos and SPA

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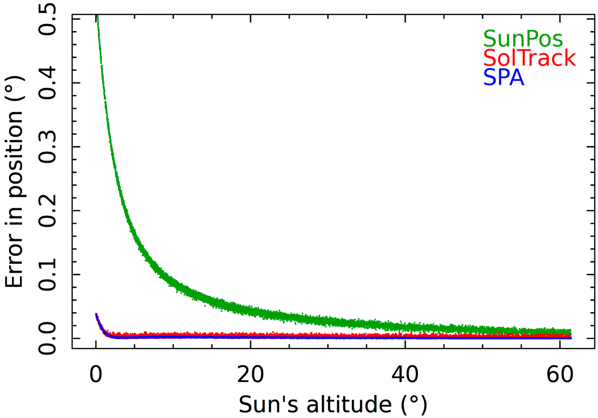
Result:

		SunPos	SPA	SolTrack
Accuracy	abs.	$0.073 \pm 0.091°$	$0.0023 \pm 0.0037°$	$0.0030 \pm 0.0016°$
	rel.	$23.9\times$	$0.76\times$	$1.00\times$
CPU time	rel.	$1.03\times$	$19.7\times$	$1.00\times$



Van der Sluys et al., 2015; in prep.

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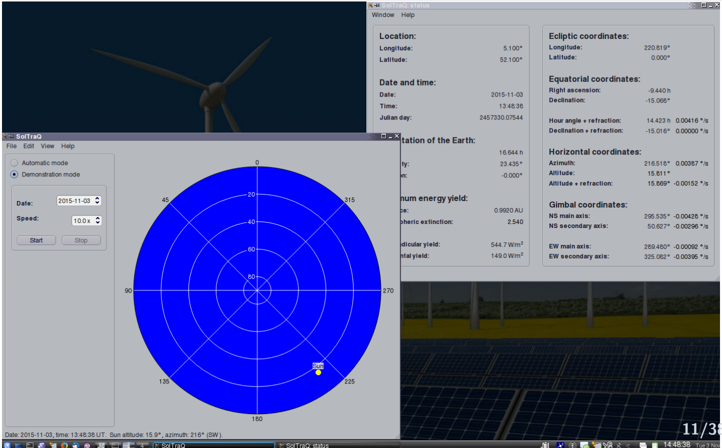
From SolTrack to SolTraQ

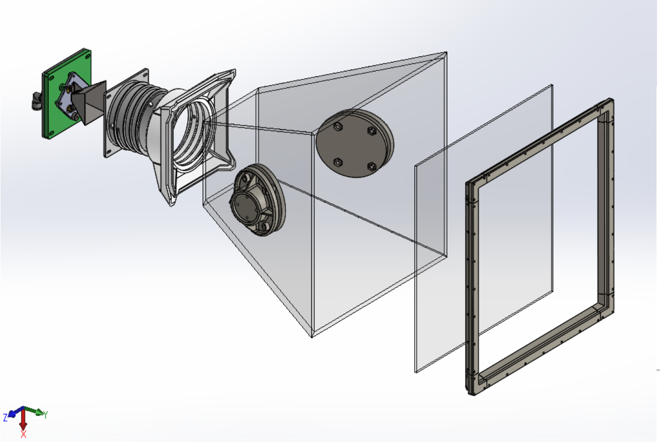
Semi-manual control

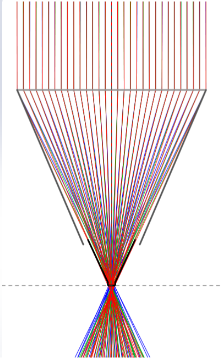
- Manual control from PC
- GUI based on Qt
- Demo-mode for bad weather/indoor demonstrations



Outline

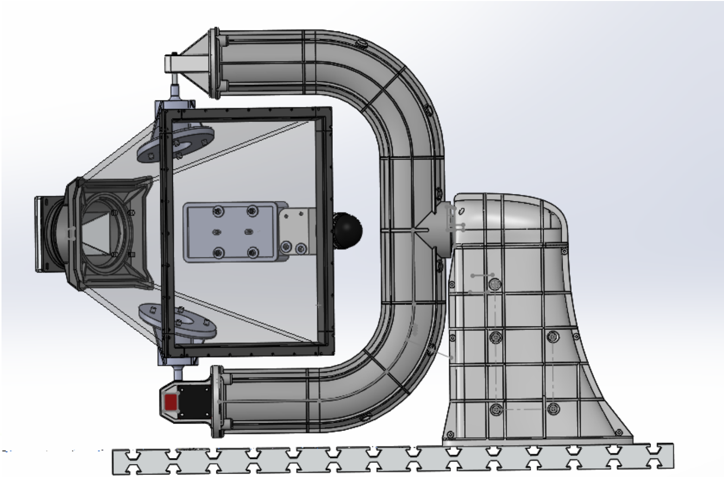
Concentrator design



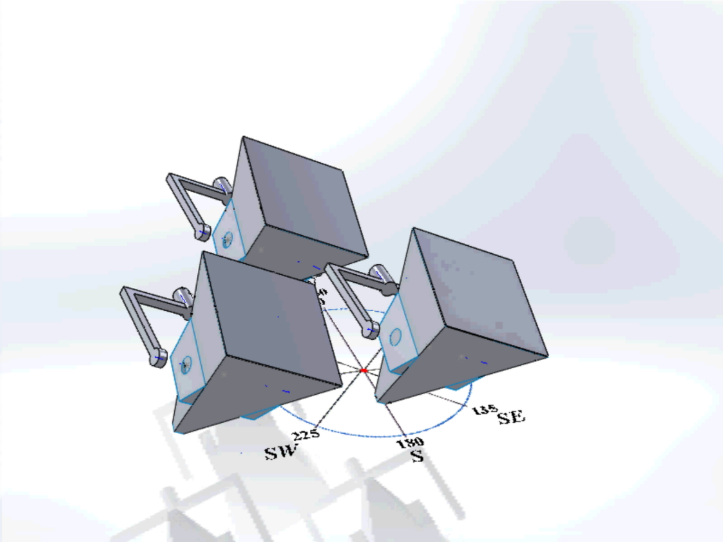


- Lens: $30 \times 30\,\mathrm{cm}$, $f = 30\,\mathrm{cm}$
- Solar cell: $1\,\mathrm{cm}^2$
- Concentration factor: $\sim 900\times$

Concentrator design



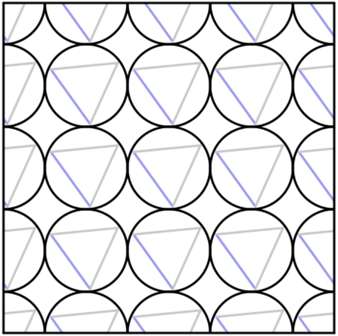
Concentrator arrays

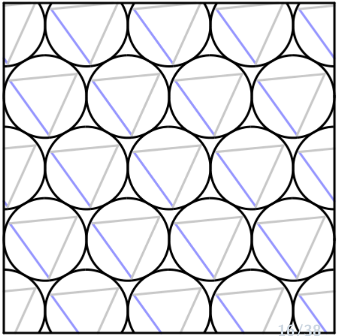


Array lattice and spacing

2D lattice for spheres of rotation

- Square
    - distance: 1.00, 1.23 or 1.60$\times$ lens size
- 'Honeycomb'
    - Row factor $\sqrt{3}/2$ closer
    - 15% more energy yield per m^2 roof (but: shading!)
    - 13% less transiting direct sunlight per m^2 roof

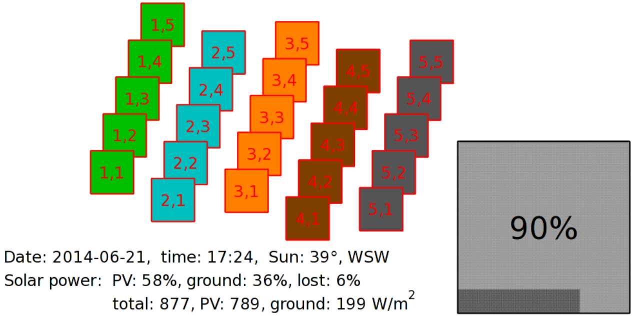




Example summer

Field of Console units on 21 June, 17:24 CEST:

- No shading; $\sim$ 977 W/m^2 for PV
- Daily 86% for PV (10.0 kWh/m^2 for 100% Sun)
- Daily 36% (max. 48%) direct light on the ground

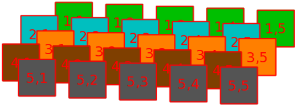


Van der Sluys et al., 2015

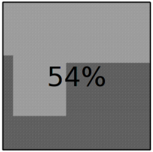
Example winter

Field of Console units on 21 December, 12:00 CET:

- Much shading; $\sim$ 267 W/m^2 for PV
- Daily 45% for PV (1.1 kWh/m^2 for 100% Sun)
- Daily 3% direct light on the ground



Date: 2014-12-21, time: 12:00, Sun: 14°, S
Solar power: PV: 53%, ground: 1%, lost: 46%
total: 499, PV: 267, ground: 1 W/m^2



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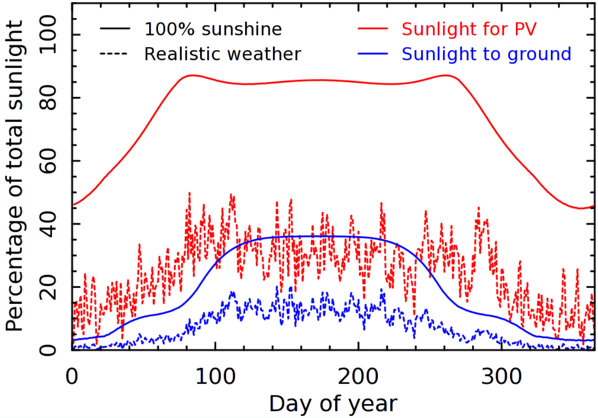
Weather data WUR

- Realistic weather: 939 kWh/m^2 sunlight (35%)
  - 767 kWh/m^2 (28%) for PV
  - 161 kWh/m^2 (9%) passes between concentrators

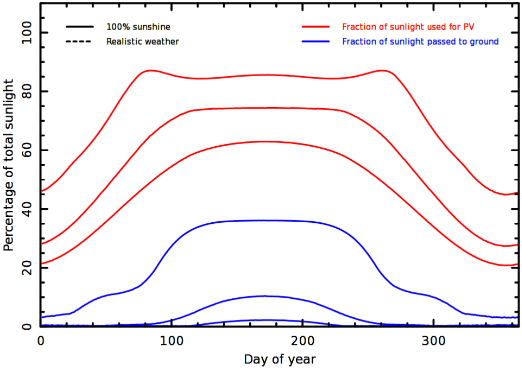


Van der Sluys et al., 2015

Weather data: met.wur.nl

Grid comparison

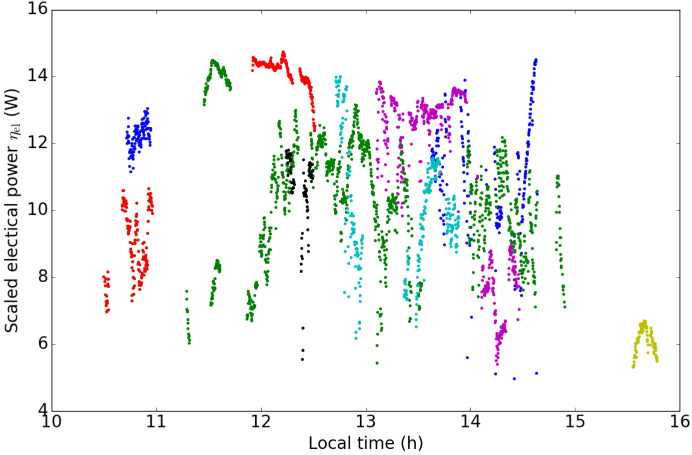
Dist.	PV/m^2	PV	Ground	Touch?	Cost/m^2
1.60×	767 kWh	80%	25%	No	100%
1.23×	624 kWh	65%	4.6%	Can	171%
1.00×	501 kWh	52%	0.9%	Will	222%



How much light do *you* want?

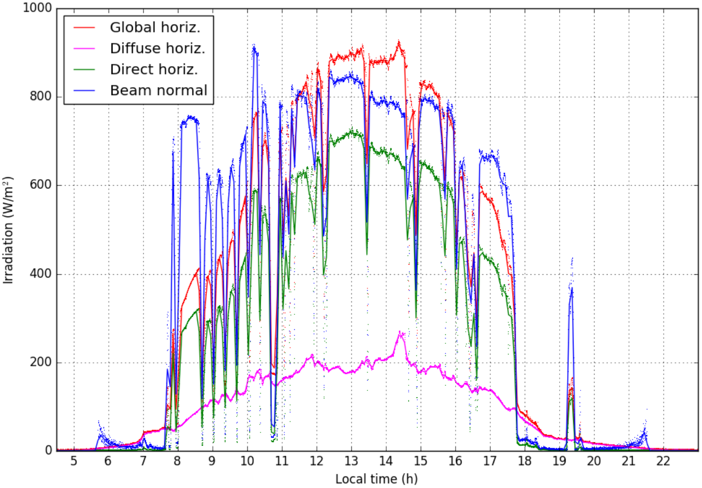
Outline

HCPV-GO yield measurements



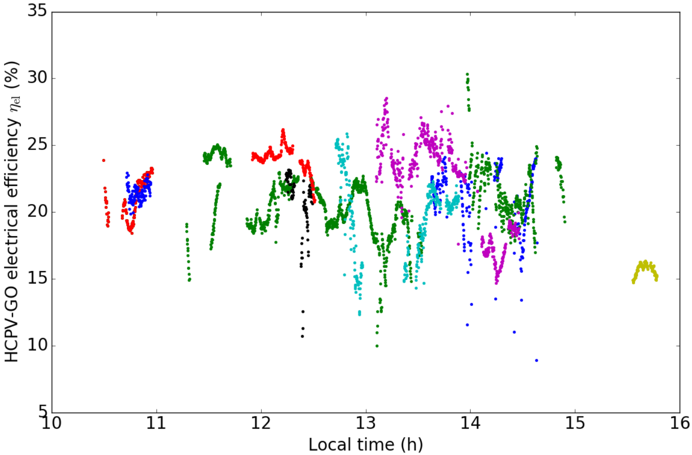
Electrical power computed from measured current

Pyranometer data



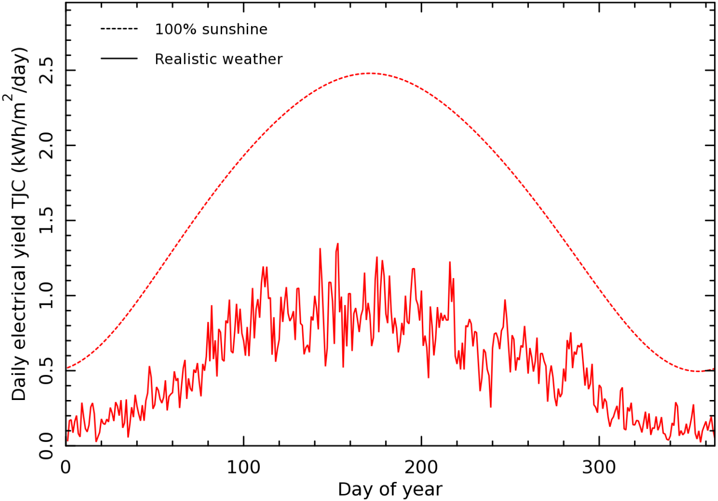
Scale yield with *beam normal radiation*

Relative yield / efficiency



- Electrical efficiency: $\sim 21.2 \pm 2.0\%$
- (Thermal efficiency: $\sim 29 \pm 4\%$)

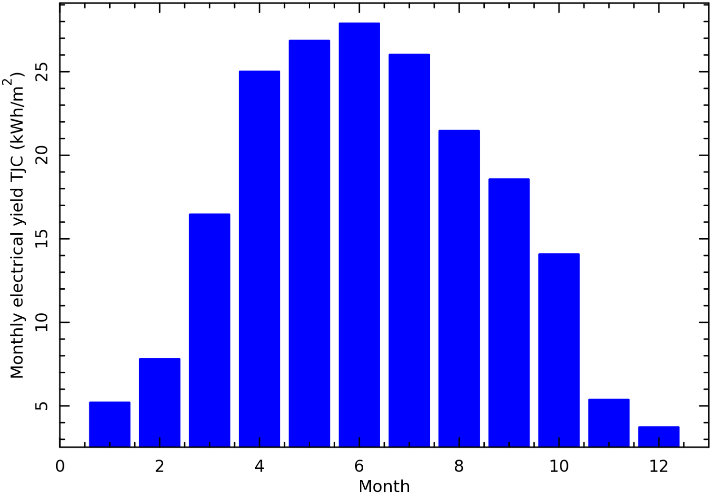
Daily yield



Based on a single cone, and an efficiency of 21.2%

Weather data: met.wur.nl

Monthly yield



Yearly electrical yield: $\sim 199\,\mathrm{kWh/m^2}$

Based on a single cone, and an efficiency of 21.2%; Weather data: met.wur.nl

Use of direct and diffuse light

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Direct light:

- 7–32% of yearly direct sunlight reaches the ground by falling through the spaces between the cones (in Arnhem)
- hence, 68–93% of direct light is blocked
- more direct light can be let through by turning concentrators by 90°

Diffuse light blocked:

- distance between units: $1.23\times$ linear size of unit (collide in case of malfunction): $\approx 28.3\%$
- distance between units: $1.60\times$ linear size of unit (never touch): $\approx 16.7\%$

Note: blocking by drive arm ignored!

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Outline

Closed-loop tracking

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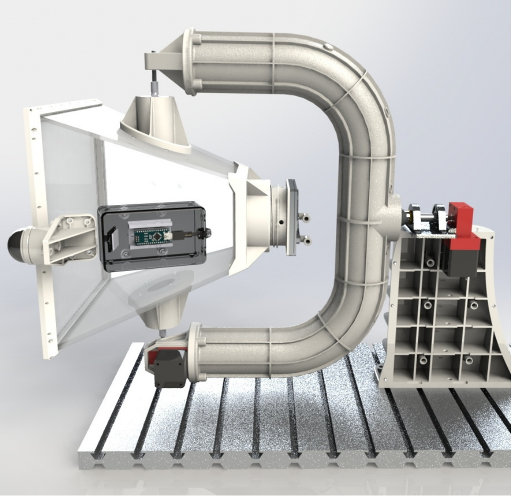
Use sensors to turn the open-loop tracking into closed-loop to compensate for:

- mechanical deformation
- backlash
- imperfect installation
- correction on SolTrack position



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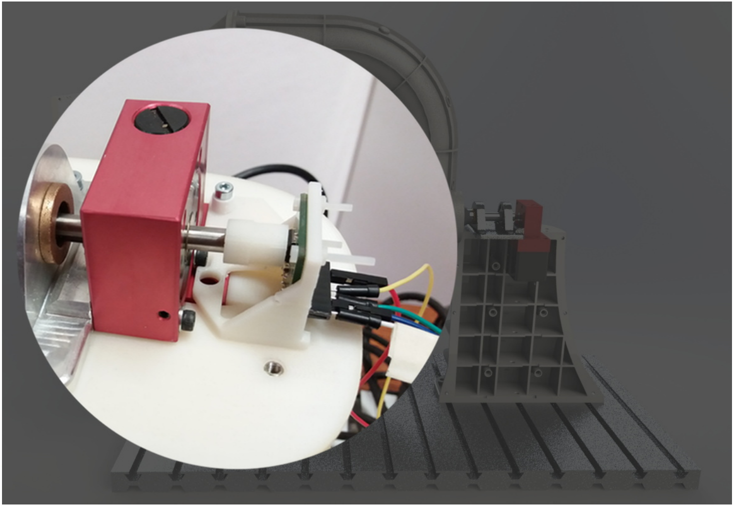
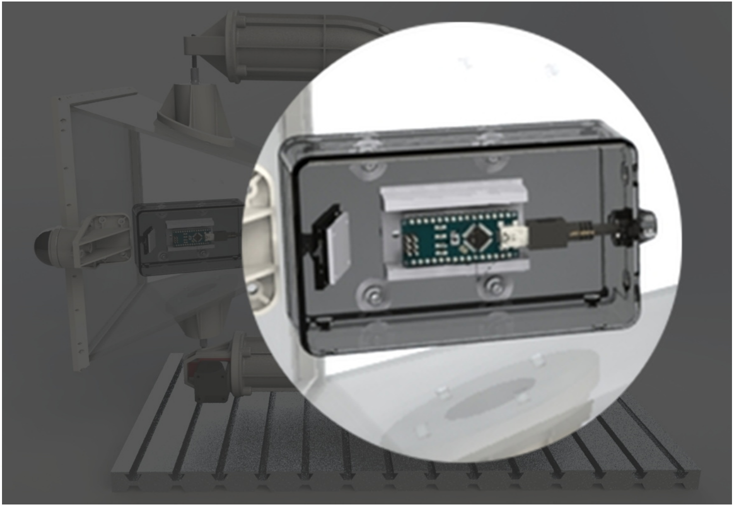
Closed-loop tracking



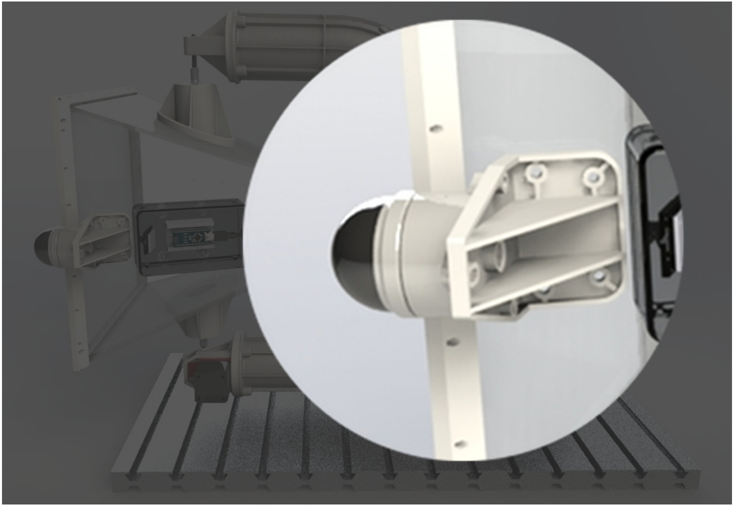
Verify motor rotation: AS5145B programmable magnetic rotary encoder

Closed-loop tracking



Verify cone orientation: ADXL345 accelerometer for inclination sensing

Closed-loop tracking



Verify orientation w.r.t. the Sun: Alitec STAR_SPS four-quadrant sensor; Lens R&D BiSon 6

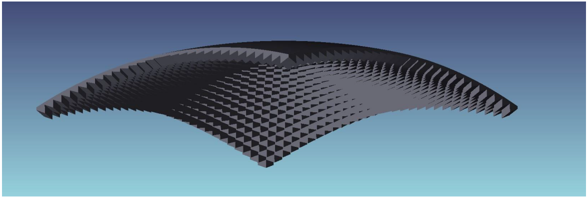
Redesigning the concentrators

Optimise optical train

- Tune primary optics, secondary optics and solar cell

Primary optics

- Concentrate more light
- Create a more homogeneous spot $\rightarrow$ more efficient solar cell
- Increase electrical yield (+20%?)

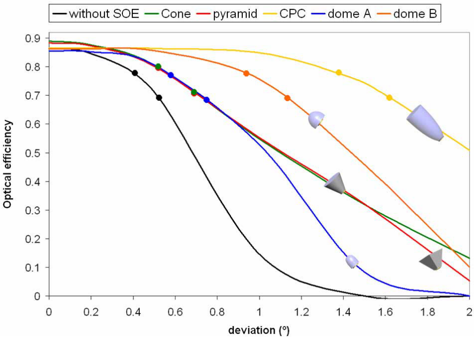


Source: NTS Optel

Redesigning the concentrators

Secondary optics

- Relax critical parameters of system (= lower cost)
- Wider acceptance angle (easier tracking)
- Perhaps yield gain?



Victoria et al. (2009)

Solar cell

- Smaller cell → lower cost?

Redesigning the concentrators

Other improvements

- More transparent design
- Maximum-power-point tracking
- Expand: single cone $\rightarrow$ array
  - wire up multiple concentrators
- Connection to public grid
- What to do with heat?

Outline

Conclusions and future work

Conclusions:

- Our concentrator has a concentration factor of $\sim 900\times$
- We have a reasonable optical system and an open-loop tracking strategy based on SolTrack
- We can achieve an electrical efficiency of at least $\sim 21\%$ and a yearly electrical yield of $\sim 199\,\mathrm{kWh/m^2}$
- In an array:
  - summer: much PV and much direct sunlight on ground
  - winter: little PV and little direct sunlight on ground
- Transparent design allows diffuse light to pass

Conclusions and future work

Next steps:

- Open loop $\rightarrow$ closed loop
  - use sensors for feedback
  - correct for imperfect alignment and mechanics
  - should result in fully autonomous operation
- Redesign optics
  - better-tuned optical train
  - reduce required tracking accuracy
  - improve electrical yield
- Single concentrator $\rightarrow$ array
  - MPP tracking
  - wire up arrays
  - connect to public grid