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SAND2010-2563P

Optical Methods Laboratories

Sandia National Laboratories and
National Renewable Energy Laboratory

Albuquerque, NM
February 8, 2010

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Department of Energy under Contract DE-AC04-94-AL85000.

Agenda

- **Purpose** (5 min; Wilkins)
- **Introduction** (10 min; Andraka)
- **Proposed lab facilities** (15 min; Andraka/Wendelin)
- **Optical Tools** (50 min)
  - LANSIR (Wendelin)
  - VSHOT (Gray)
  - Distant Observer (Jorgensen)
  - SOFAST (Andraka)
  - TOPCAT (Diver)
  - Dish Alignment Methods (Andraka)
  - Heliostat Alignment Methods (Yellowhair)
  - SolTRACE (Wendelin)
  - CIRCE (Andraka)
  - Flux Mapping (Andraka)
- **Open Discussion** (all)
- **Closing Remarks** (10 min; SNL/NREL/DOE)

Introduction

Chuck Andraka
SNL

Vision

- Optical Leadership
  - Analysis and Optical Design
  - Characterization
    - Components
    - Systems
  - Alignment/Field Tools
    - Prototypes
    - Production
  - Problem solving
  - Facet options
  - Opto-structural interactions
- Optics are key
  - Heart of CSP, half of system cost, key to efficiency
  - Lack of optical expertise
  - Transition to production
  - Transfer of tools to industry

Value

- Optical engineering lacking
  - Good ME's, EE's, Controls, Civil
  - Optical issues differ from lasers and lenses
  - Too much floundering
- Tools needed
  - Turnkey for industry
  - Faster for production
  - Robust tools and training
- Direct impact on cost
  - Time in fixtures vs. # of fixtures
- Optics -> Efficiency -> Performance -> Cost
  - ASME paper

Value of Labs Leadership

- Optical expertise
  - Modeling and design
    - Highest performing dish systems
    - Extensive hardware experience
  - Alignment
  - Flux mapping
  - Problem solving
- Recognition of issues
  - Industry often assumes optics are easy
  - Systems laboratory = systems view
- Cooperation with industry
  - Not “laboratory sandbox”
  - Crying out for help

Addressing Industry Issues

- **Speed**
  - Current tools are laboratory grade
  - High rate production needed
    - Alignment
    - QC characterization
- **Accuracy**
  - Existing methods sub-optimal
  - Direct impact on performance and cost
  - Efficiency -> Performance -> Cost
- **Usability**
  - Improved UI's and FEA interfaces
  - Ruggedness and flexibility
  - Computational engines are fine
- **Cost** – Facet options

Proposed Optical Methods Laboratory

SNL

Sandia National Laboratories

- Cross cutting optical methods laboratory
  - Continue ongoing efforts
  - Leverage cross-cutting opportunities
    - Dishes have impacted troughs and heliostats
    - Trough work feeding back to dishes
    - Explosion in industry partners
- Emphasis on transition from Lab to Production
- Hardware, software

Sandia Physical Space

- Current development lab
  - Hallway in receiving bay
  - Uncontrolled lighting
  - Collection point for Stuff
  - Only indoor location with suitable length
- Proposed
  - T-building
  - 20x60 feet

Sandia Approach

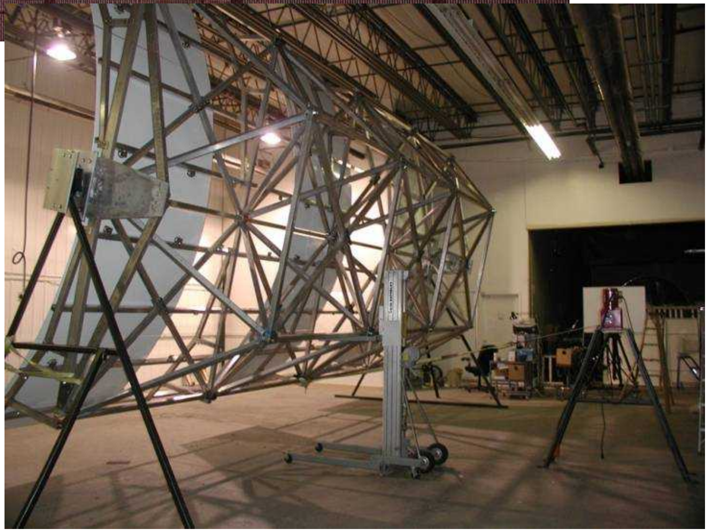
- Responsive to industry requests
- Continue work on cross-cutting tools
  - Rapid alignment of heliostats, dishes, and troughs
  - Factory and field characterization
  - Analysis tools and packages
- Facet development
  - Not a current immediate need of industry
  - Eventual direct impact on cost

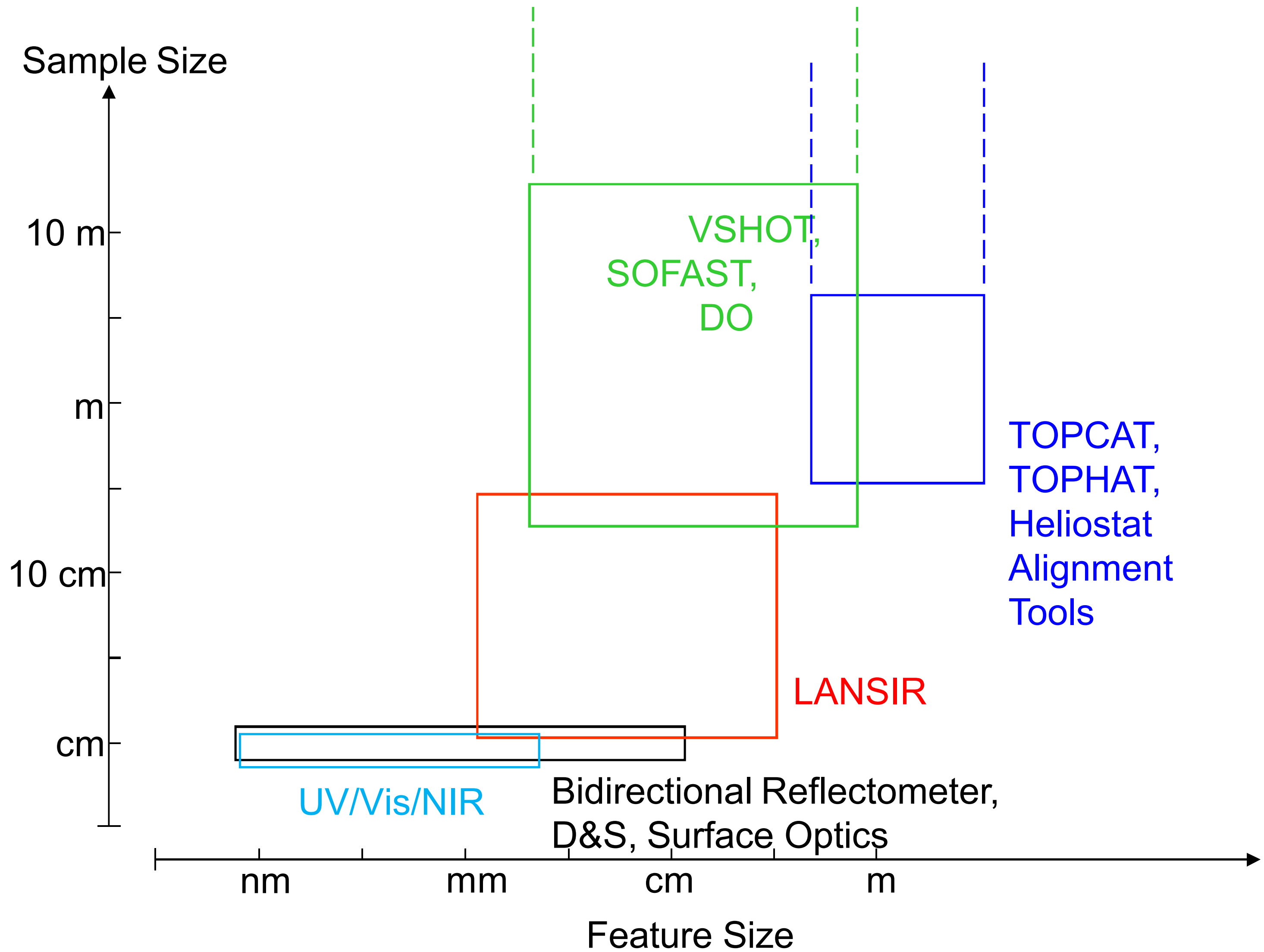
Proposed Optical Methods Laboratory

NREL

NREL Optical/Structural Characterization Facilities

- Current Facilities
  - Mesa Top Test Facility
    - Capabilities
      - On sun optical testing
      - VSHOT
      - DO
  - Joyce Street Facility
    - Capabilities
      - VSHOT
      - DO




Sample Size
10 m
m
10 cm
cm
VSHOT,
SOFAST,
DO
TOPCAT,
TOPHAT,
Heliostat
Alignment
Tools
LANSIR
UV/Vis/NIR
Bidirectional Reflectometer,
D&S, Surface Optics
nm
mm
cm
m
Feature Size

Optical Characterization Techniques/Methods (relative to troughs)

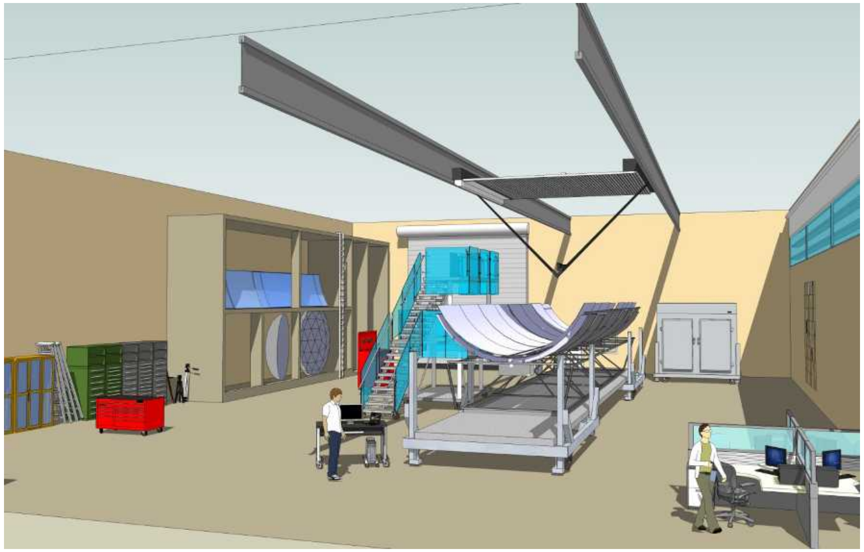
ABENGOA SOLAR

Legend:
- ++ Well suited
- + Workable
- - Not suited
- na Not Applicable

General Category	Method	Reflector Coupon	Panel	Assembly Jig	Assembled Structure	Module	Module + Receiver	Collector	Field	Plant
Reflector Material Optical Properties	Reflectometer, portable	++	++	na	na	+	+	+	-	-
	Spectrometer, portable	++	++	na	na	+	+	+	-	-
	Spectrophotometer	++	na	na	na	na	na	na	na	na
	Accelerated weathering chamber	++	na	na	na	na	na	na	na	na
Surface Contour (Slope/Position)	Coordinate Measuring Machine (CMM)	-	+	-	na	na	na	na	na	na
	VSHOT	na	++	na	na	+	-	na	na	na
	Photogrammetry	na	++	++	++	++	+	+	-	-
	Deflectometry	-	++	na	na	+	+	na	na	na
	OPAL Reflector Analysis	-	++	na	na	+	+	na	na	na
	Laser tracking	na	+	++	++	++	++	-	-	-
	Laser radar	na	++	++	++	++	++	+	-	-
Panel/Receiver Alignment	Distant Observer	na	+	na	na	na	++	++	++	na
	Theoretical Overlay Photographic (TOP)	na	na	na	na	na	++	++	+	na
	Laser alignment	na	+	na	na	++	+	na	na	na
Flux Measurement	Parascan	na	na	na	na	na	++	++	+	-
	Digital Image Radiometer	na	na	na	na	na	+	+	-	-
Power	Thermal test loop	na	na	na	na	na	++	++	++	++

NREL Optical/Load Characterization Facilities

- Future Facilities
  - ESIF
    - 7-8000 Square feet/30' ceiling
    - Previously funded via non-CSP resources, ready by late 2011
    - Potential Capabilities
      - VSHOT, Photogrammetry, IR Laser Radar, Deflectometry (SOFAST), DO
      - Structural Load Testing
      - Thermal Cycling/optical characterization of large optics



- Future Facilities (cont.)
  - Solar Technology Acceleration Center (SolarTAC)
    - Existing outdoor test facility founded by Xcel Energy/MRI/Sun Edison/Abengoa Solar
    - EPRI/NREL new members, others in process

    - Work with industry participants to provide testing capabilities and leverage off of industry infrastructure to develop and demonstrate new technology
    - Testing Capabilities
      - Optical testing
      - Contour testing, TOPCAT, DO
      - Structural load testing

Overview of Future NREL Lab Facilities

Summary

- Optical performance strong driver in LCOE
    - Especially critical as higher temperature & concentration technologies develop.

- Labs have played and should continue to play an important role in providing characterization techniques to industry.

- Successes such as Abengoa, SkyFuel, Acciona, SES, Infinia direct result of this role.

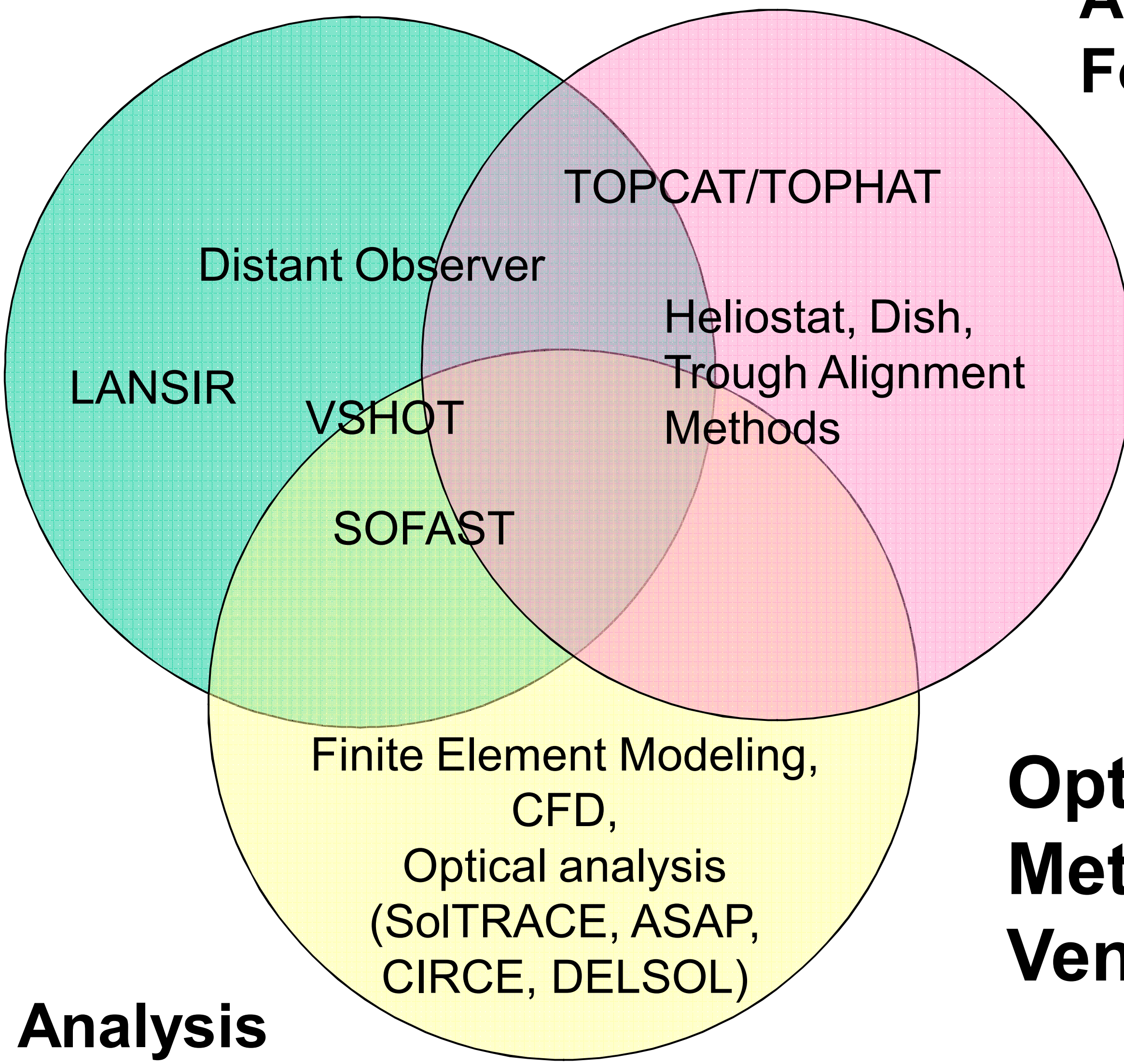
- Labs cannot keep up with current industry demand.

- This will not change in the future except to increase.

- New concept/technology development aimed at reducing LCOE should be part of our effort.

Optical Tools

Summary of Tools



Optical Methods Venn Diagram

Characterization Tools

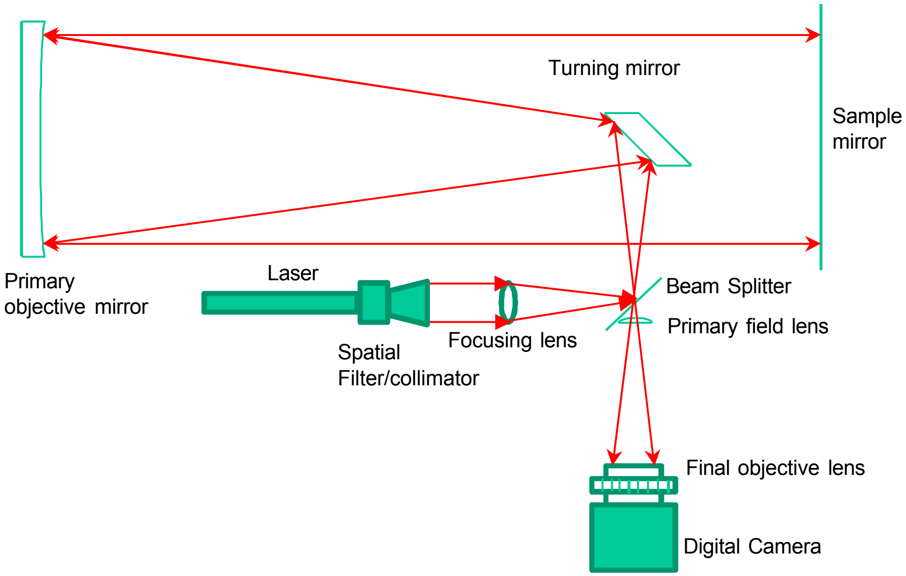
LANSIR

Tim Wendelin
NREL

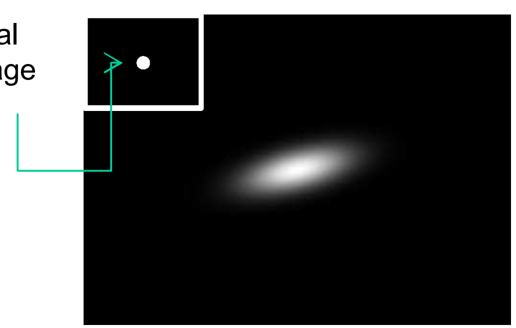
Large Aperture Near Specular Imaging Reflectometer (LANSIR)

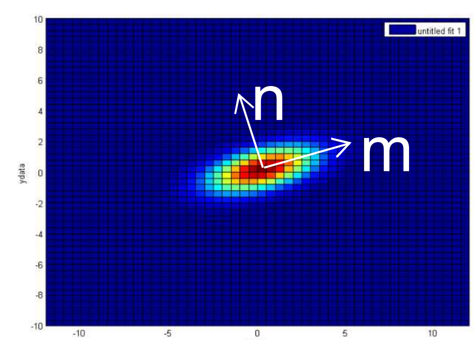
- How does it work?
  - General principle
    - Measure specular beam spread of optical materials/substrate structures
  - What is the output?
    - Statistical distribution parameters which are then used to calculate specular reflectance (optical models/SAM)

$$\rho_s(\theta) = \rho_{2\pi}(1 - e^{-0.5(\theta/\sigma)^2})$$



Ideal Image





Large Aperture Near Specular Imaging Reflectometer (LANSIR)

- Applications
  - Scale
    - Intermediate spatial regime between microscopic/dielectric properties and contour error properties
  - Laboratory instrument
  - Provides important data to optical/systems models
  - How does this tool fit in the "toolbox?"
    - Currently fills a hole in our toolbox

Strengths and Limitations

- Fills a hole in our collective toolset
- Industry support: Alcoa, 3M, SkyFuel, Abengoa, others
- Provides data as a function of sample area and sample tension
- Fast, easy
- Provides real data for input to optical models and systems models
- Any material/substrate configuration, tensioned, non-tensioned

- Currently monochromatic
- Currently normal incidence

Future Improvements

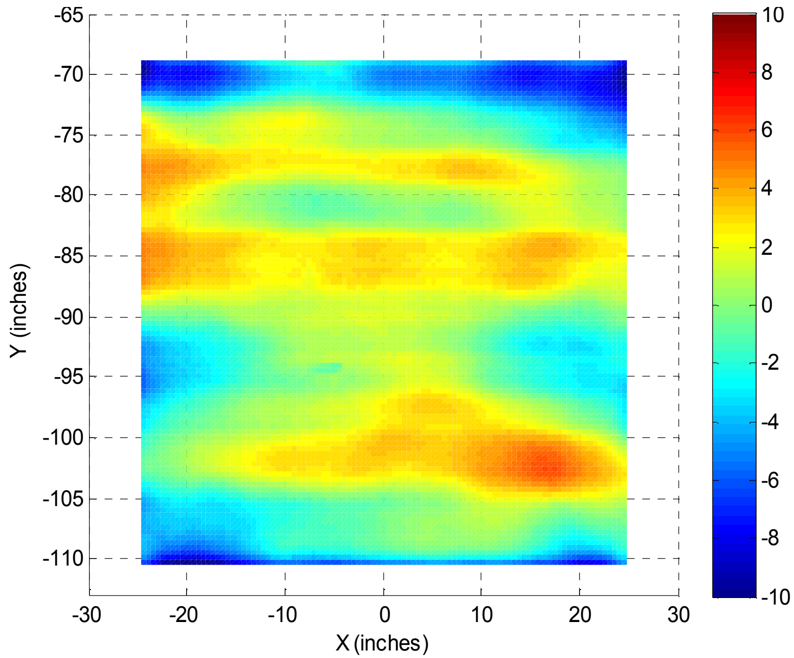
- Add spectral capability (solar spectrum)
- Add variable incidence angle capability
- Add curved sample capability
- Field Tool

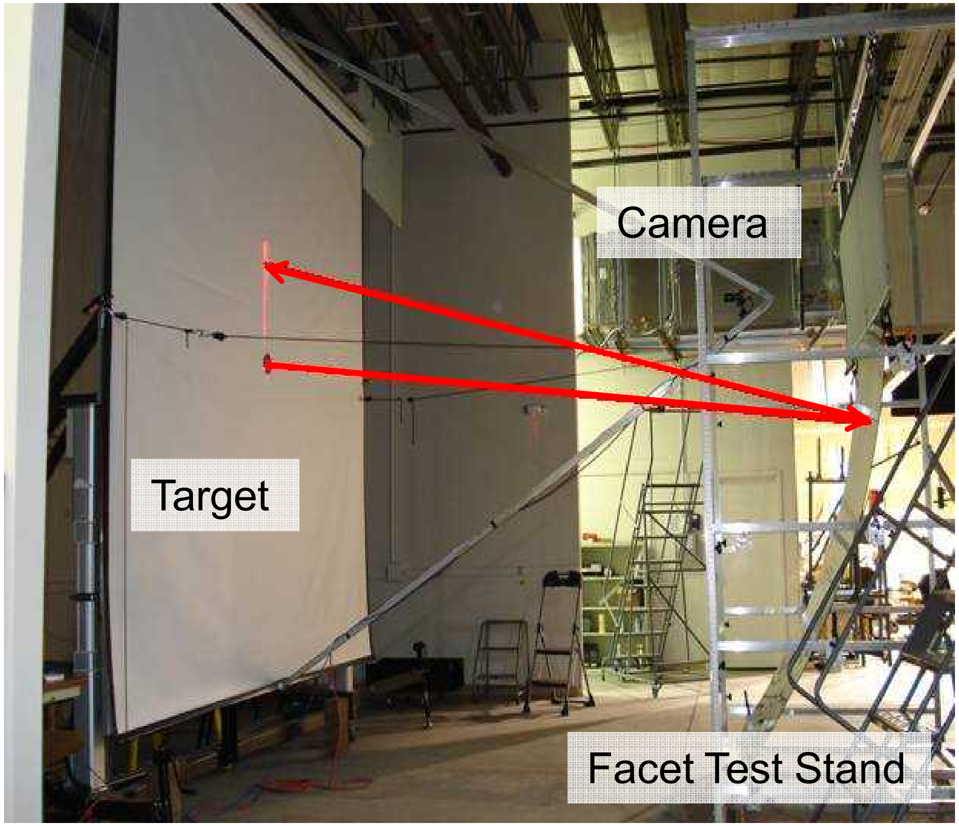
VSHOT

Allison Gray
NREL

Description

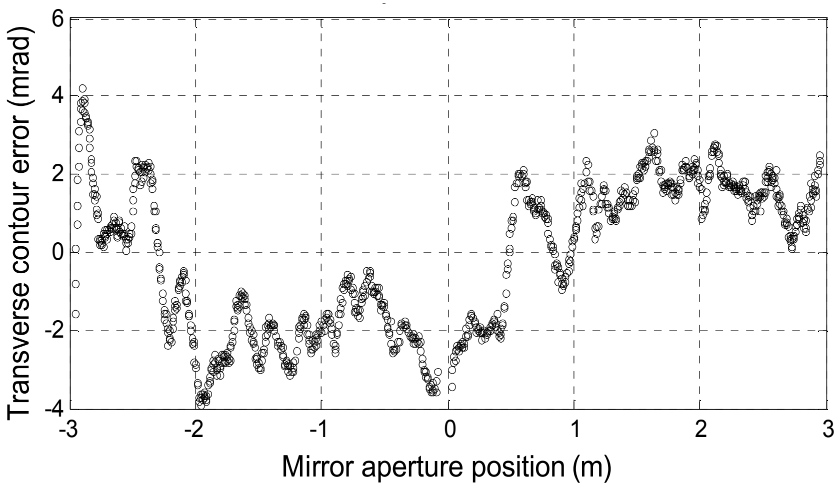
- How does it work?
  - Laser scans a mirror
  - Laser is reflected back to a target
  - Camera is used to image the laser return spot

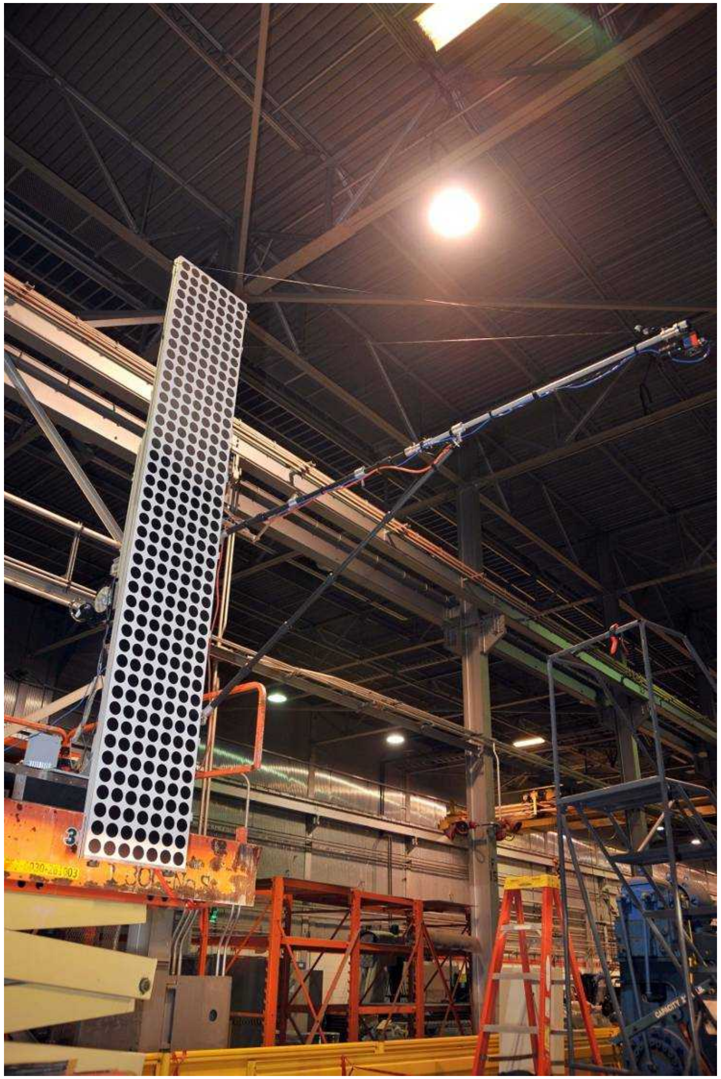




Applications

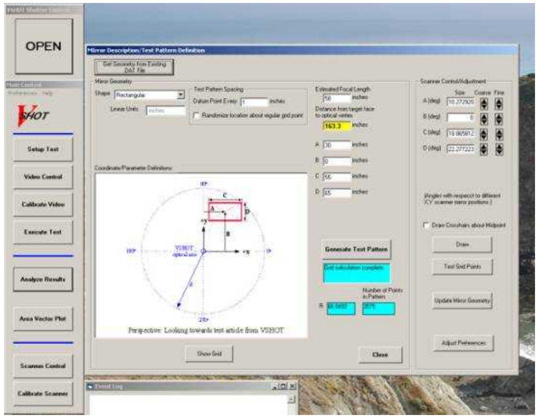
- Test both individual facets and entire systems
- Development tool for both lab and field applications
- Measures surface slope deviation from ideal
- Interfaces with SolTrace





Strengths and Challenges

- Capable of testing most geometries
  - Linear, point focus, flat facets
- User friendly GUI



- Has been licensed to 2 industry partners
- Can test standard mirrors and minimally reflective surfaces (e.g. glass)

- Not a full field maintenance tool
  - 2-5 hour setup time in the field
  - Large target is unstable under light winds
  - 2-4 hours to test one trough module in the field (14 scans)

- Point by point data collection

- Limited to 30,000 data points per test

Future Improvements

- Software conversion (Visual Basic 6 to MatLAB)
- Allow for testing in more than one position
- Decrease test time
- Reduce laser recalibration time
- Increase amount of data per test

Distant Observer

Gary Jorgensen
NREL

How Does It Work?

- General principle
  - An observer that is sufficiently distant from a parabolic trough and aligned with the optical axis will see the reflection of the receiver tube filling the aperture
  - Variety of aerial platforms possible
- What is the output?
  - Intercept factor
  - Collector alignment
  - Slope errors

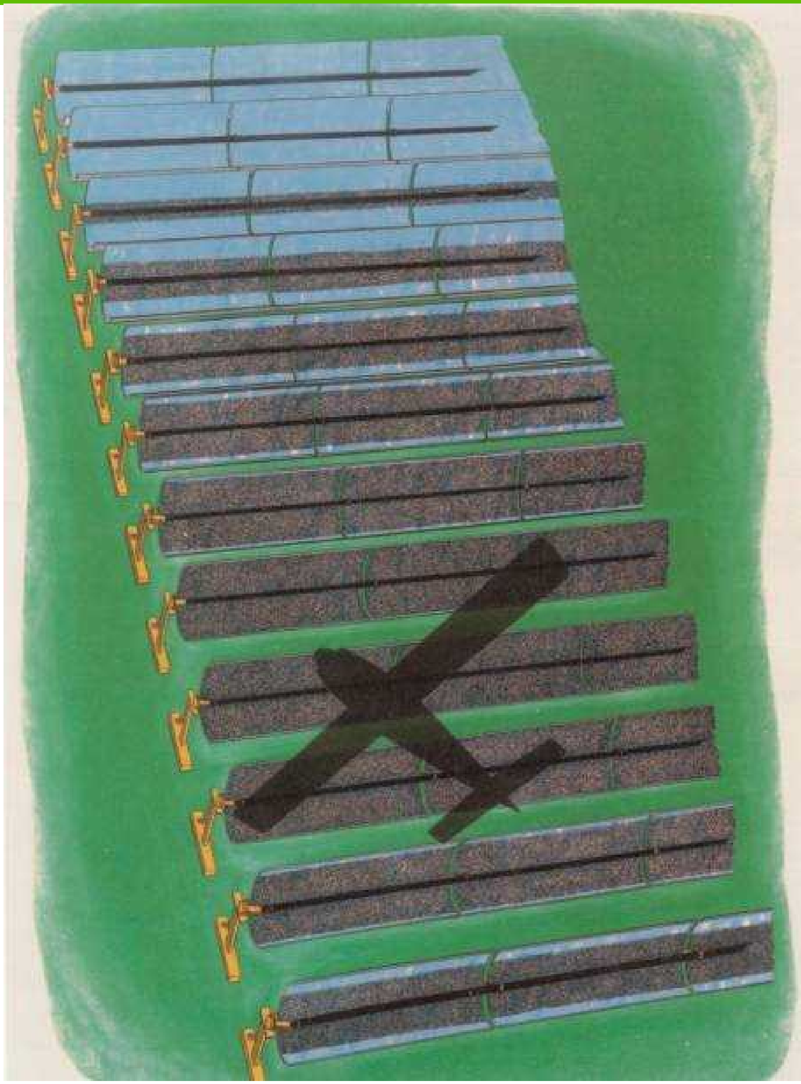
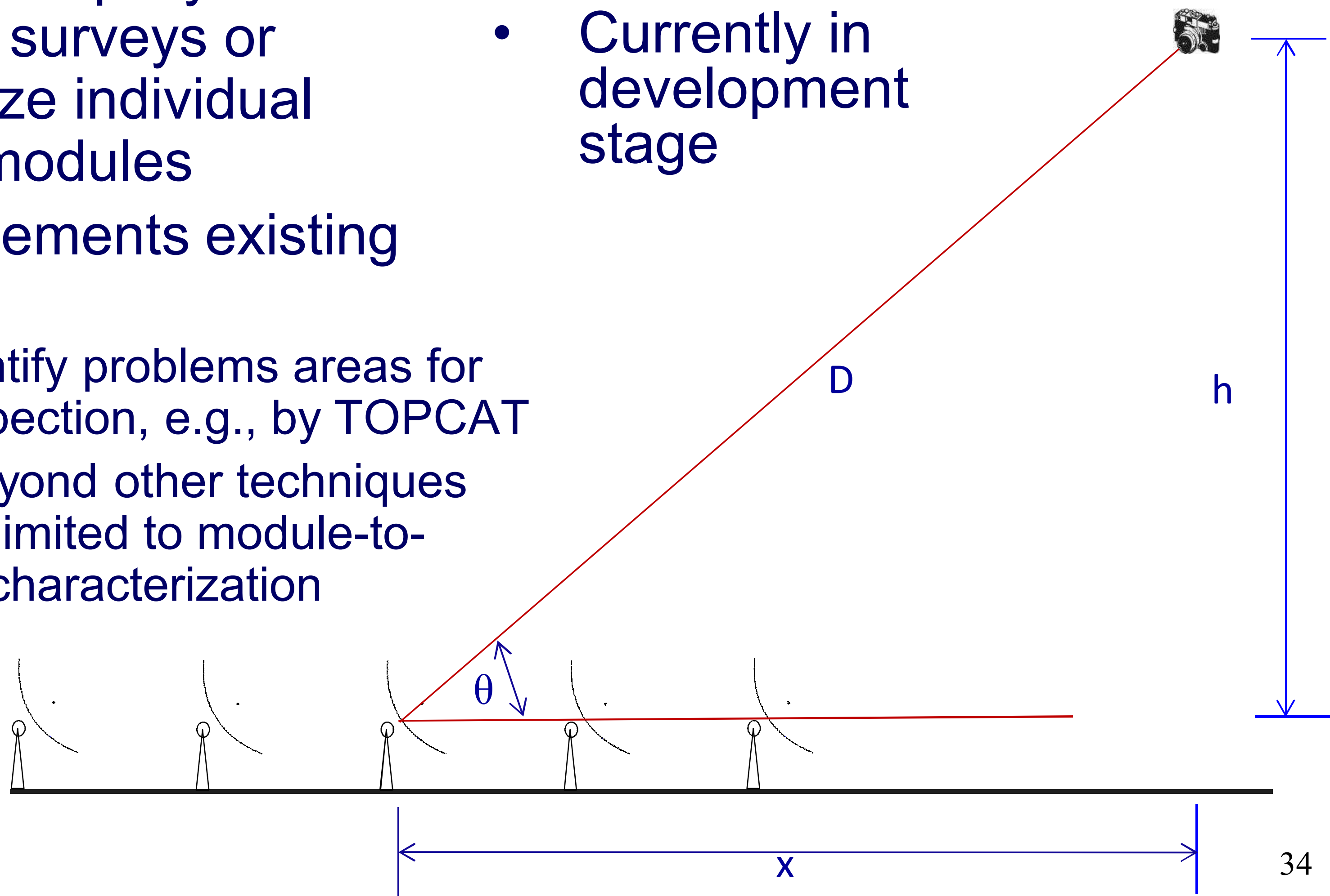


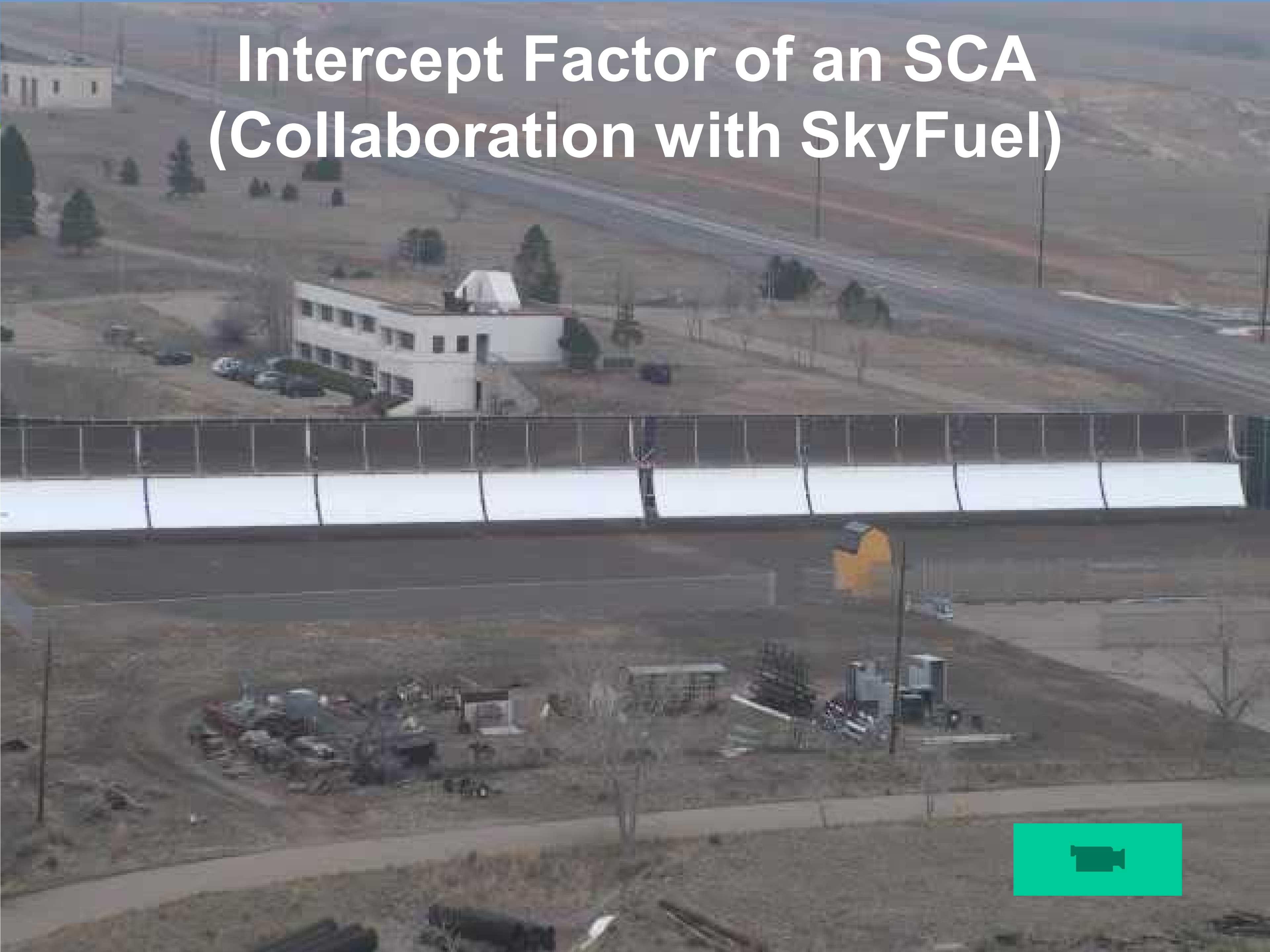
Figure from: Wood, R. L., “Distant Observer Techniques for Verification of Solar Concentrator Optical Geometry”, 1981.

Applications

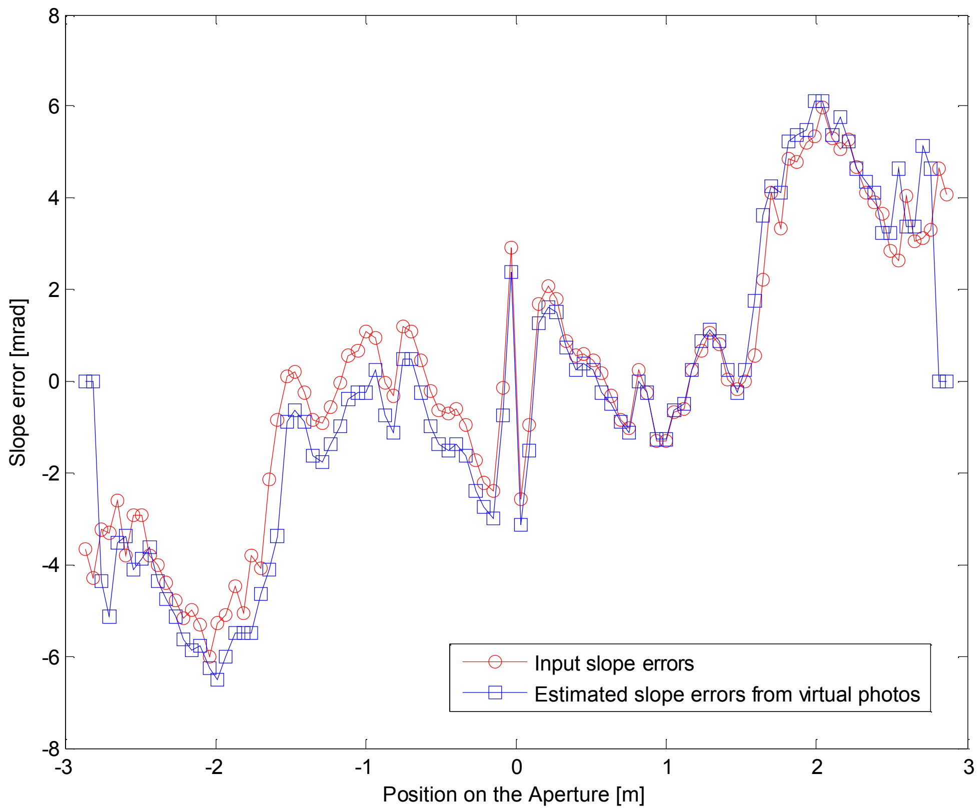
- Scale: Can rapidly conduct large field surveys or characterize individual collector modules
- DO complements existing tools
  - Can identify problems areas for finer inspection, e.g., by TOPCAT
  - Goes beyond other techniques that are limited to module-to-module characterization
- DO is a field tool
- Currently in development stage

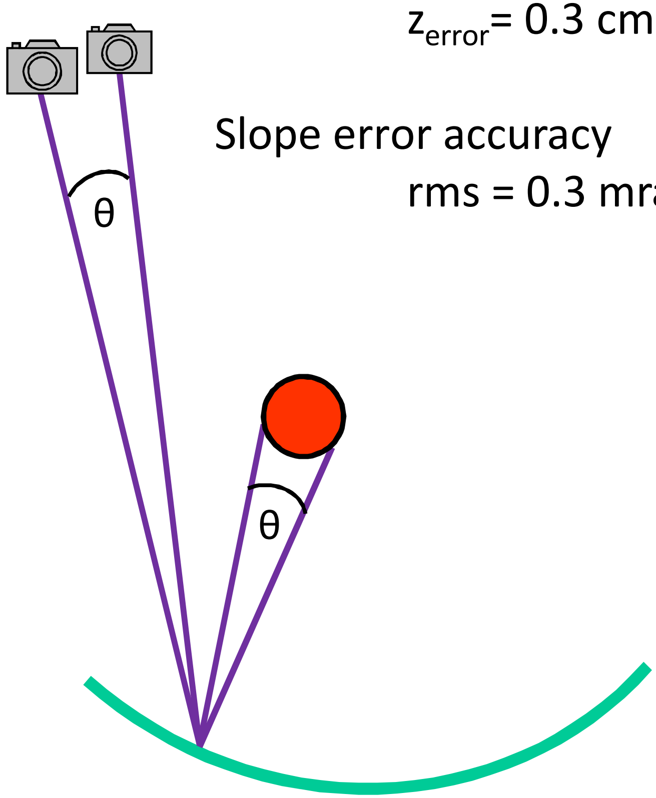


Intercept Factor of an SCA (Collaboration with SkyFuel)



Concurrent Determination of Receiver Position and Concentrator Slope Error





Computational Example

Photos every 0.5 mrad

Receiver position accuracy

x_{error}= 0.2 cm

z_{error}= 0.3 cm

Slope error accuracy

rms = 0.3 mrad

Strengths

- Provides assessment of:
  - Optical quantities
  - Installation quality
  - Environmental effects
  - Tracking errors
  - Receiver heat loss
- Very fast technique
- Operating orientations
- Minimizes down time
- Strong industry interest
- Low cost, simple hardware; quick set-up

Challenges

- Requires large number of rapidly acquired digital images
- Image analysis is complicated
- Tight error tolerances for camera position and pointing accuracy
- Determination of when on-axis

Future Improvements

- Off-site field assessments
- Ability to perform close-in field (& lab?) inspections
- Much quicker determination of concentrator slope errors
- Receiver IR imaging

- Resolution of aerial photography and image processing challenges
- Validation

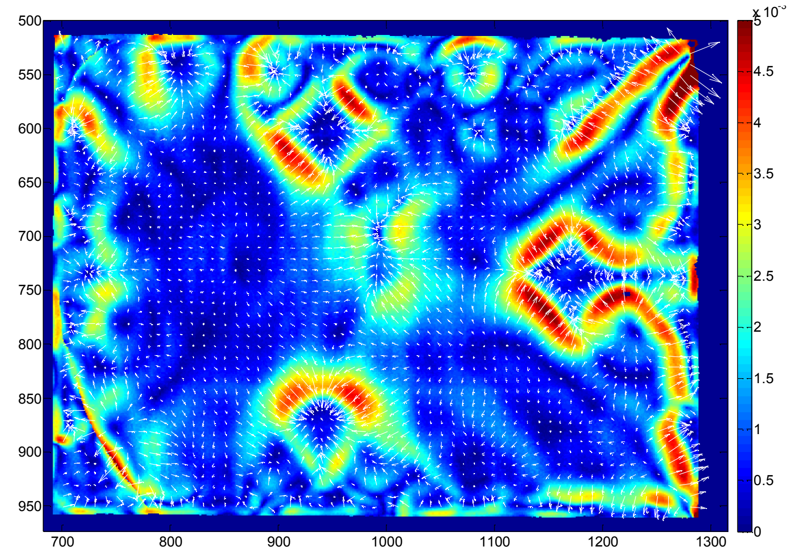
Collaboration with Abengoa Solar; Cameo, CO

SOFAST

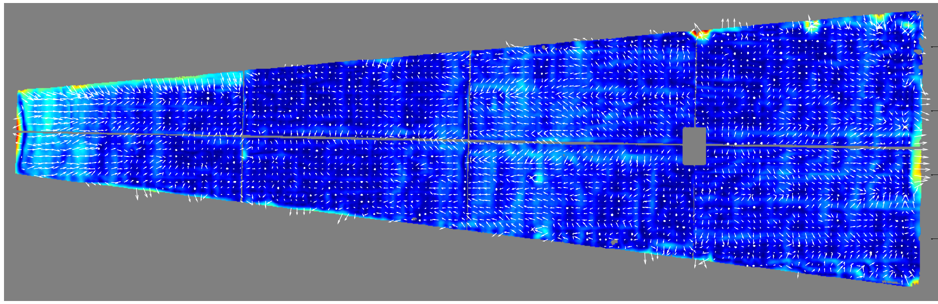
Chuck Andraka
SNL

Description

- Measures surface slope profile of facets
  - Fringe reflection or Deflectometry
  - Detailed map of surface slope and errors
    - Typically 2mm square pixels
    - 600,000+ points in 15 seconds



- Applications
  - Facet development
    - Deployed at Tower Automotive
  - 100% characterization in production
  - Direct tie to analytical models



Strengths and Weaknesses

- Fast
  - 600,000+ points in 15 seconds
- Complete characterization
  - Places facets into analytical framework
  - Compare to design and fitted surfaces
- Low cost
  - Less than $10K complete setup

- Currently limited to specific facets
- Currently does not characterize complete dish
- IP issues
- Everybody wants it

Future Improvements

- Generalize facet
- Extend to segmented systems (dishes)
- Speed (factor of 3 relatively straightforward)
- DLL interfaces for industrial use
- Extend to heliostats
- Extend to troughs
- Resolve IP issues
- Full error analysis

Alignment/Focusing Tools

TOPCAT

Rich Diver
SNL

Theoretical Overlay Photographic Collector Alignment Technique (TOPCAT)

Description:

Photographic image analysis techniques are used to quickly and accurately characterize alignment and specify adjustments

Impact:

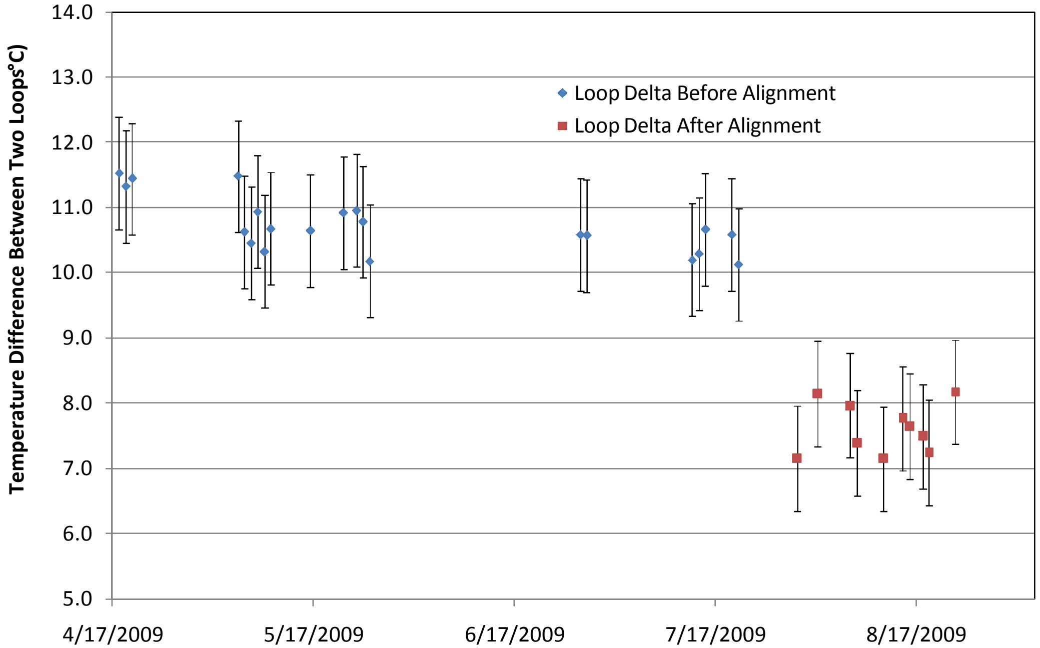
- Only practical approach for measuring trough alignment
- Eliminates alignment errors on existing and future parabolic trough collectors
- Potential large increase in performance of existing plants with minimal cost
- Enables quality control and improved performance in new collectors designs
- A key enabler for 10¢/kWh trough electricity

Theoretical image overlaid on to carefully surveyed photographic images to guide alignment

TOP Alignment Fixture

Strengths and Weaknesses

- Strengths
  - Aligns an entire SCA
  - Accounts for receiver position and module-to-module errors
  - Worksheets prescribe corrections
  - Fast and low cost
  - Proven & cost effective
  - ~ 10 to 20 ¢/Watt implementation cost
- Weaknesses
  - Custom fixture hardware difficult to transfer to industry
  - Accuracy limited ~ 0.5 mrad



Summary loop delta results from SEGS VIII

Future Improvements

- Improve automation of image analysis
  - High quality camera lenses
  - Incorporate advanced edge finding algorithms
- Additional performance measurements
  - Measurement of benefits at Next Era Energy and Cogentrix plants
- Transfer technology to industry

Dish Alignment Methods

Chuck Andraka
SNL

Description

- Optical target with coherent images
  - 100m lookback typical
  - Predicted pattern on printed target
  - 0.25 to 1.0 mrad RMS alignment error
- Applications
  - Prototype installations

Strengths and Weaknesses

- Flexible tool
- Low cost
- Deployable
  - SES
  - Brayton
  - ADDS
- Can account for structural flex

- Slow: 2-4 hours/dish
- Accuracy depends on facet accuracy
- 100m line of sight needed
- Operator interpretation
- Susceptible to dish motion

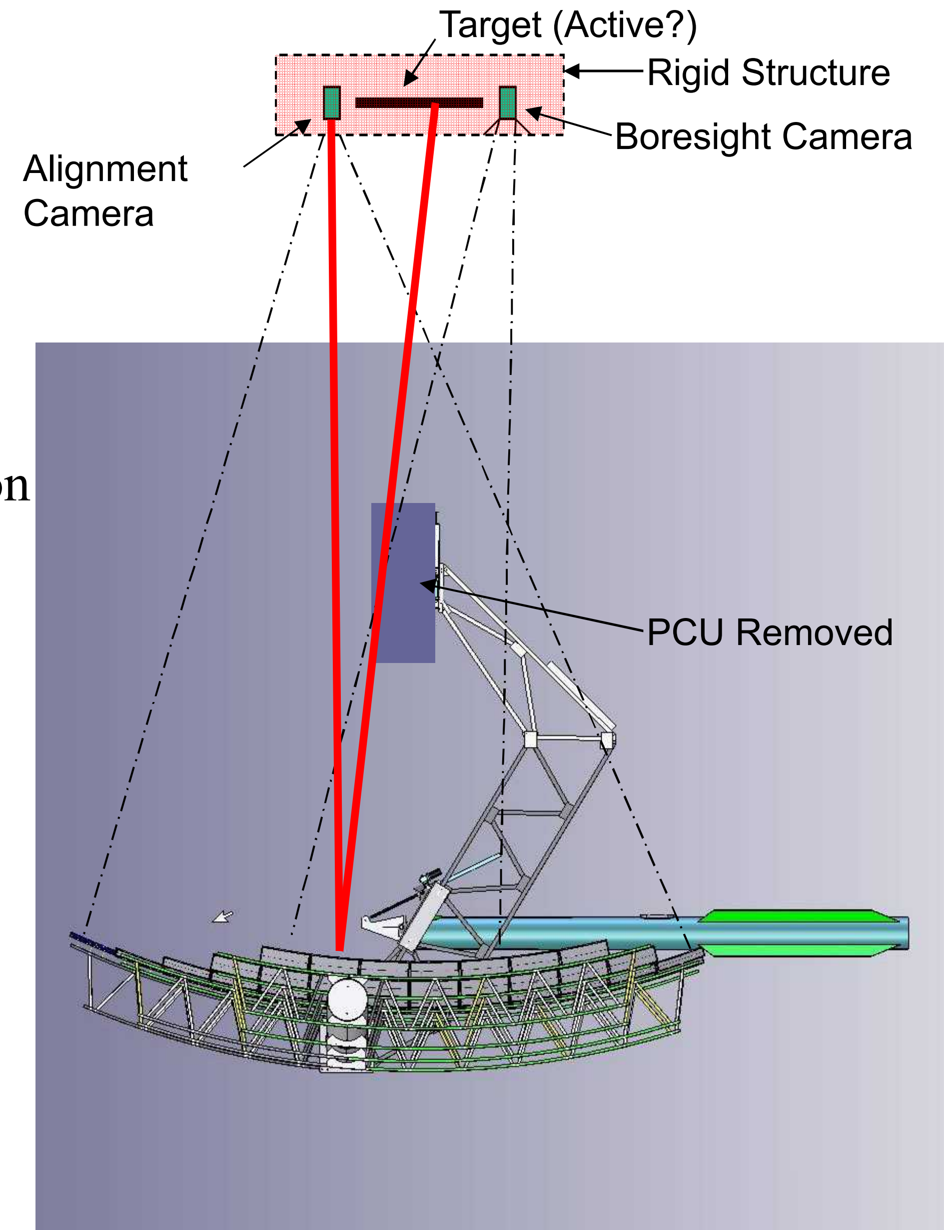
Future Improvements

- Flexible target generation tool
- Better connections to CIRCE for alignment strategy development
- Deployments

SOFAST Alignment

Description

- Fringe Reflection method applied to alignment
  - Image entire dish at once
  - Calculate facet fitted shape/position
  - Indicate adjustments
    - Automated tools
    - Feedback devices
- Applications
  - Production alignment
  - Heliostats, Dishes



Strengths and Weaknesses

- Fast
  - Estimated 15-25 minute Takt time
- Accurate
  - Estimated 0.125 mrad or better
  - Limited by structure/tool interactions
- Rapid setup
  - Self aligning, boresighting
- 2-f method
- Vertical alignment allows screw access

- Still in development
- Extension to troughs not clear
- Controlled light environment best

Future Improvements

- Develop and evaluate tools
- Verify robustness to off-normal conditions
- Integrate with actuation tools (SES)
- Deploy at SES (Summer 2010)
- Optimize for speed
- Generalize
  - Other dishes
  - Heliostats
  - Characterization
- Field re-alignment tool (truck mounted

Heliostat Alignment Methods

Julius Yellowhair
SNL

Heliostat Alignment Methods

- Some heliostat alignment methods we looked into:
  - Gauge blocks
  - Inclinometers
  - Photogrammetry
  - Camera look-back
  - Laser projections
  - Deflectometry/Fringe Reflection
  - TOPHAT
  - Target Reflection

Limited in various ways

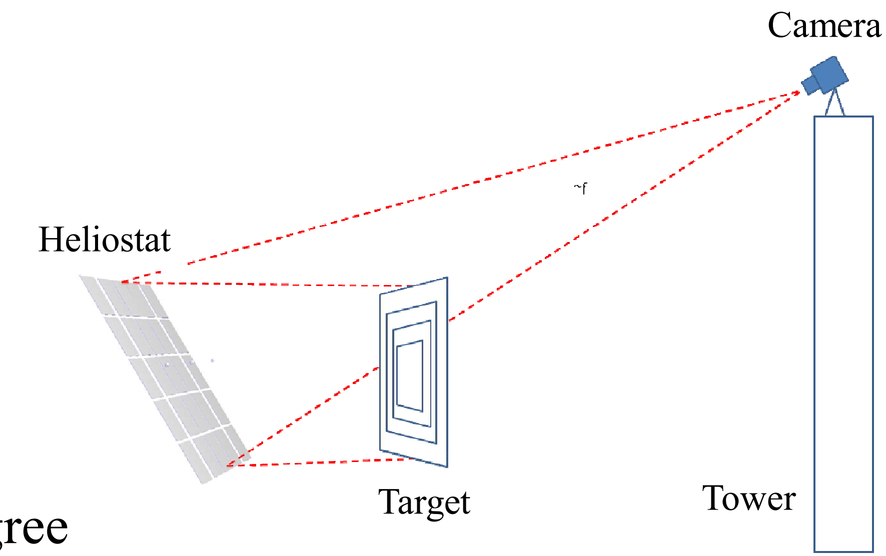
Methods that have been used in the past

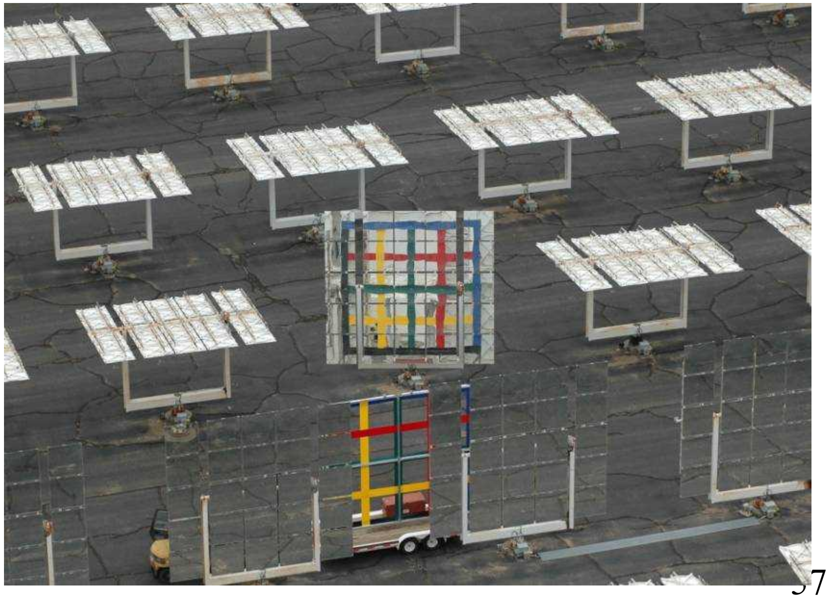
New methods we plan to develop

Methods we believe that have potential

Description

- How does it work?
  - A camera, located on top of the tower, views a target in reflection through the heliostat
  - Image of the target shows the degree of heliostat (facets) misalignment
- Applications
  - Full heliostat alignment
  - Demonstrated in the field
  - Low cost and provides measurement accuracy and efficiency; needs further development for usability





Target Reflection Method

Strengths

- Minimal amount of hardware (low cost)
- Aligns entire heliostat w/o moving the test set-up (efficiency)
- Nothing too complex (usability)
- Facet focus correction possible

Weaknesses

- In development stage
- Won't be as accurate as deflectometry, but we can do some trade offs

Demonstration of Target Reflection Method

Before alignment

After alignment

Future Improvements

- Implement wireless communication
- Implement image processing
- Implement calibrations
- Develop mechanics for fast adjustments of bolts (?)
- Look at other ways to improve efficiency

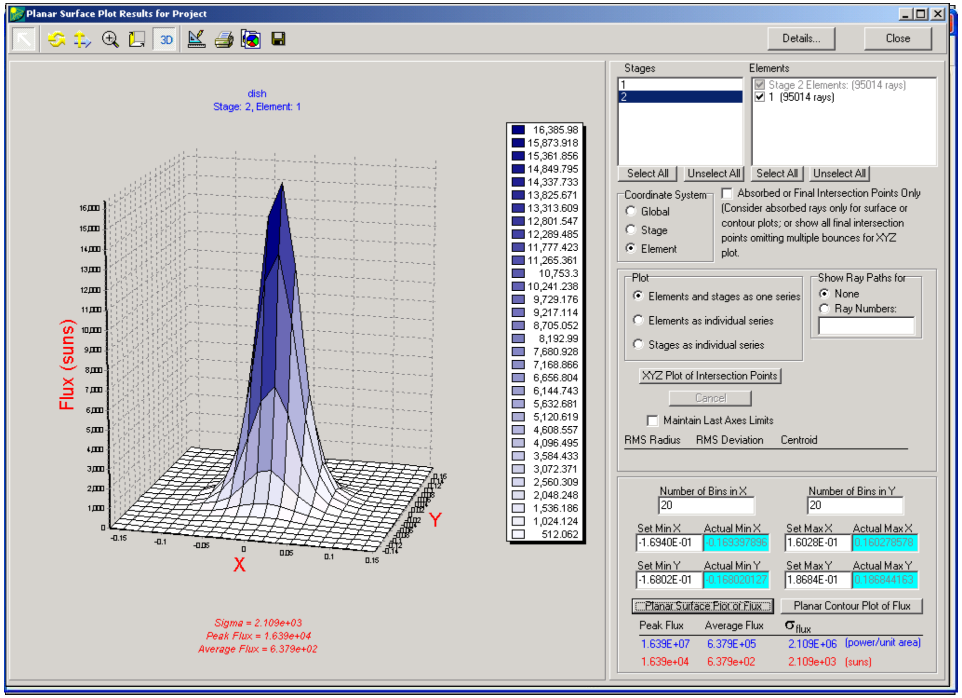
Analysis Tools

SolTRACE

Tim Wendelin
NREL

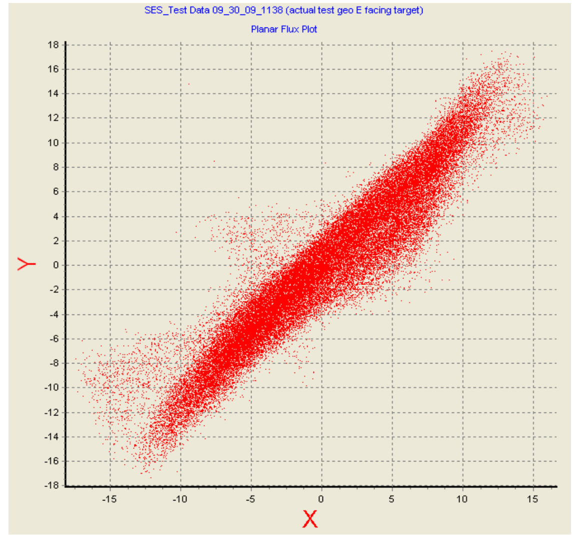
How does it work?

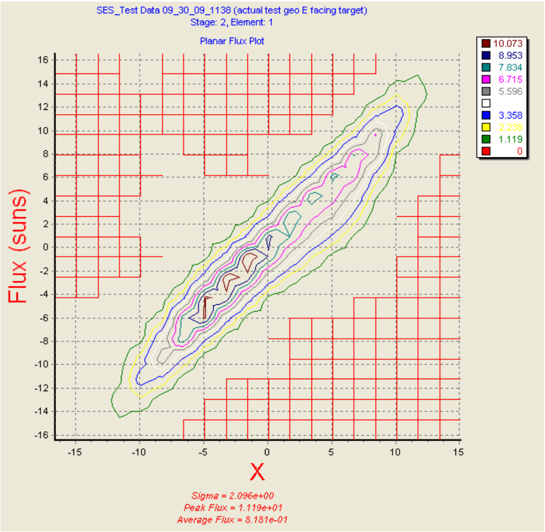
- Optical Modeling Code based on ray tracing
- Input
  - User specified optical geometry
    - Analytical or measured (VSHOT, SOFAST?)
    - Examples: Troughs, Dishes, Furnaces, Fresnel, other
  - User specified sun definition
    - Sun Shape
    - Location, time of day, day of year
- Output
  - Ray distributions at use specified surfaces
  - Flux density profiles at user defined surfaces
  - Optical performance parameters
  - Raw data for export to other analyses

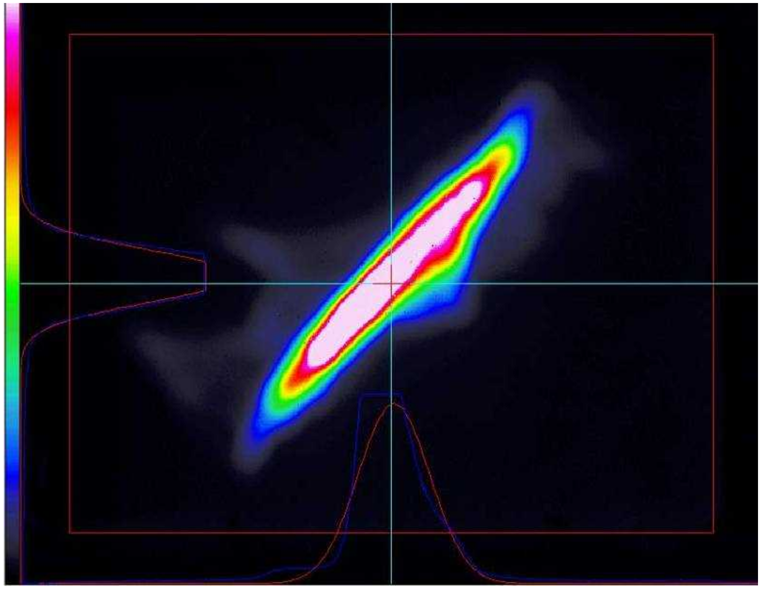


Applications

- Simulate optical performance of measured surfaces
- Simulate systems for input to other e.g. SAM
- Design tool for cost effective technology development







Strengths and Weaknesses

- Windows based
- Easy to use
- Optical/sun geometry virtually infinite
- Large library of surface descriptions - both analytical and measured
- Variety of output options
- Reflection and refraction

- Non GUI geometry description
- Incomplete implementation of Fresnel equations
- Point in time
- User support an issue

Current and Future Improvements

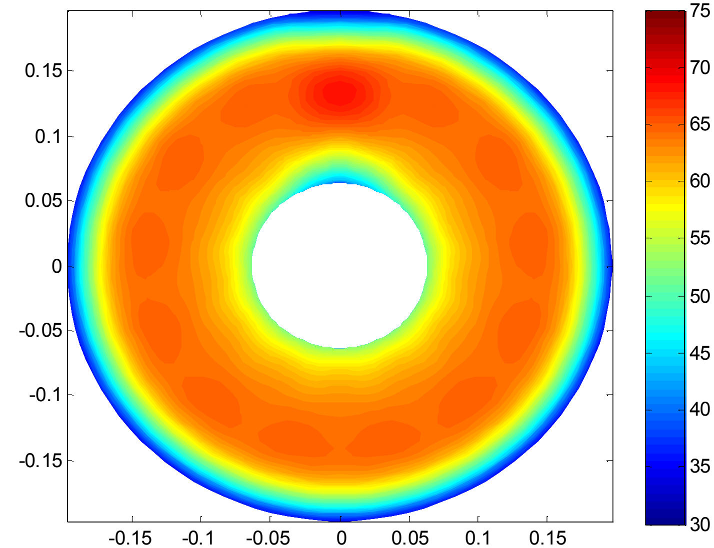
- Code converted to C++
- 1st level code optimization
- 1st cut, almost an order of magnitude decrease in processing time
- Scripting capability to allow dynamic modeling of systems
- Will be interfaced to Solar Advisor Model
- Solid modeling input geometry definition
- Spectral capability/enhanced materials properties

CIRCE

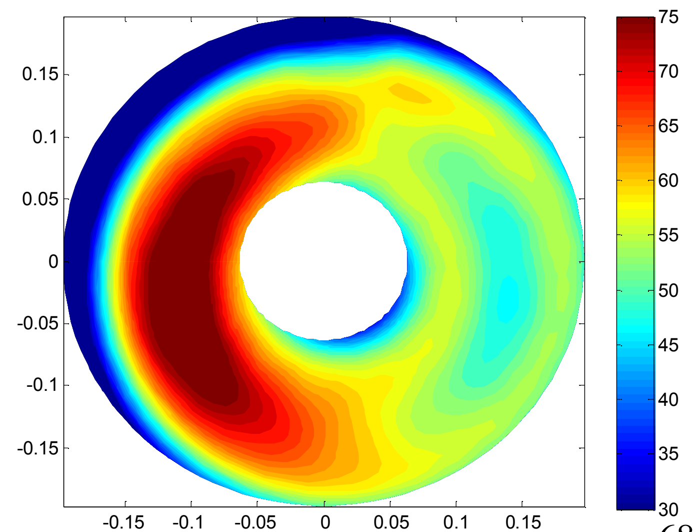
Chuck Andraka
SNL

Description

- Dish Analysis Program
  - Convolved sunshape and error distribution provides speed
  - Detailed analysis of optical performance



- Applications
  - Initial dish design
  - Error bounds analysis
  - Field issue root cause analysis
  - Alignment strategy development
  - System optimization
  - Conversion of fluxmap data to receiver data
  - Flexible, fast modeling of dish systems



Strengths and Weaknesses

- Fast: Convolution Optics (6-10 sec)
- Accurate: Calibrated to real world
- Adapted to current needs
  - Real data input from SOFAST and VSHOT
  - Flexible cavity design

- DOS interface
- Limited to dishes, near focal area
- Non-intuitive input layout is difficult to grasp

Future Improvements

- Re-order i/o information to a more logical progression
- Pre/Post processing tools to explore key features
- More direct tie to FEA for structural interactions
- Off-focus modeling
- Trough modeling
- GUI interface to reduce i/o development and learning

Flux Mapping

Chuck Andraka
SNL

Description

- On sun characterization tool
  - Flat water-cooled target
  - Image reflected energy
  - Provide fluxmaps of system
- Applications
  - Tower, dish
  - End-to-end verification of design, build, align process
  - Diagnostic tool
  - In-field verification
- Industry interest
  - SES
  - Brayton
  - Infinia

Strengths and Weaknesses

- Simple tool
- Deployable
  - SES
  - Brayton Energy
- Low cost

- Archaic equipment
- Flat plate flux only
- Difficult to use software
- Proprietary software and hardware
- No easy interface to solar tools

Future Improvements

- Turnkey system in MatLab
  - Modern camera
  - Safety interlocks
  - Target actuation integrated for programmable test runs
    - Substantially speeds data runs
    - More reliable data (eliminates tracking changes)
    - Makes it feasible for production field checks
- Target Actuator
  - Accurate positioning speeds setup
  - Repeatable positioning

Open Discussion

Closing Remarks

OPTICAL TOOLS

- **Purpose of Optical Tools**
  - Reduce cost
  - Reduce cost
  - Reduce cost
- **High performance optical designs needed to reduce trough electricity cost to 9¢/kWh**
  - Enables doubling aperture with standard 70 mm receivers (2X trough)
    - Cut number of receivers and other components in half
    - Cut heat loss in half
  - Enables the use of higher temperature working fluids
    - Concentration ratios of current troughs too low to justify 500°C operation
    - Higher heat loss at elevated temperatures negates much of the benefits
- **Advanced optical design is key to reducing cost**
  - More accurate mirrors needed
    - Improved designs, e.g., structural facets (Optical/advanced manufacturing lab)
    - Rapid, accurate mirror characterization for feedback
  - Optical alignment needed
  - True closed-loop tracking sensors needed
  - Need to address wind and gravity induced optical errors (deflectometry and numerical analysis)
- **Industry is not going to take the initiative**
  - Too risky
  - Nearer term focus on project development
  - Have plenty of opportunities at current costs
  - A lot of ignorance and misconceptions