Ph. D. Research

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14. ABSTRACT

A major requirement for using a solar propulsion system is the proper placement of the focal spot on the thruster absorber plane. Without proper placement of the focal spot, solar energy is not transferred to the propellant gas or at worst case, a significantly smaller proportion of the incident energy is transferred to the gas.

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Agenda

- Introduction
- Problem Definition
- History and Previous Work
- Proposed Solution
- Experimental Equipment
- Model and Simulation
- Summary

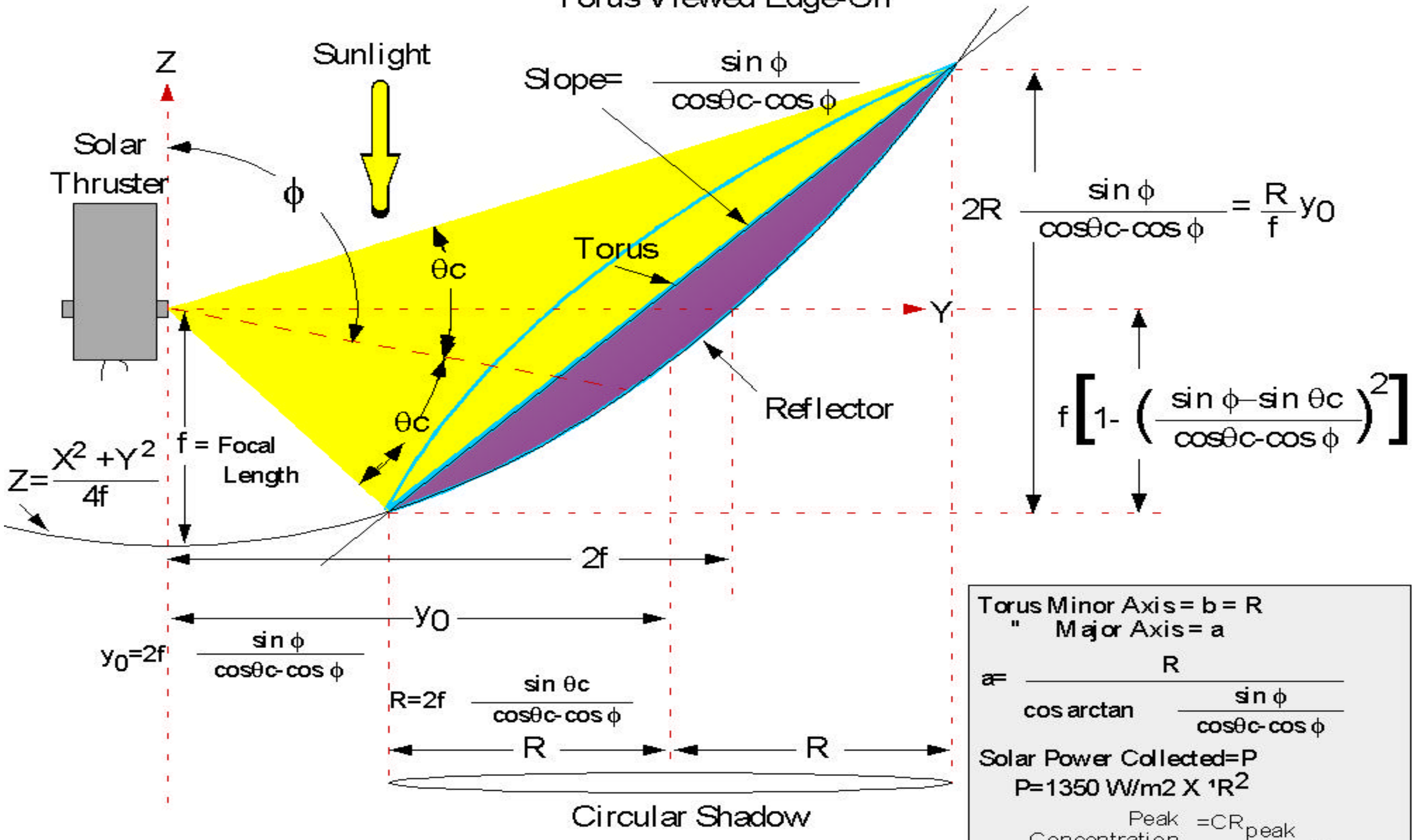
Introduction

- A major requirement for using a solar propulsion system is the proper placement of the focal spot on the thruster absorber plane. Without proper placement of the focal spot, solar energy is not transferred to the propellant gas or at worst case, a significantly smaller proportion of the incident energy is transferred to the gas.

Solar Thermal Spacecraft Configuration

Geometry For Spacecraft

Solar Thruster Concentrator;
Torus Viewed Edge-On



Torus Minor Axis = b = R
" Major Axis = a

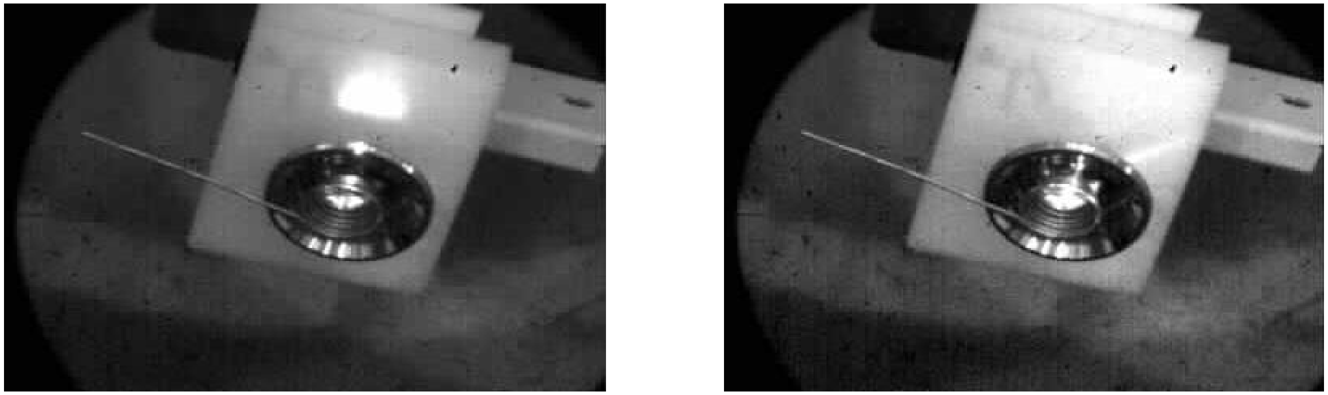
$$a=\frac{R}{\cos \arctan \frac{\sin\phi}{\cos\theta c-\cos\phi}}$$

Solar Power Collected=P
$P=1350\ W/m2\ X\ {}^{\prime}R^2$

Peak Concentration Ratio $=CR_{peak}$
$=46{,}000\sin^2\theta c$

Problem

Determine location of solar focal spot on a visually complex thruster absorber and secondary concentrator. Visual complexity compounded by specular reflection from the secondary concentrator and by the fact that the camera is moving with the concentrator.



Basic Problem Solution Concept

- **Use Charge Coupled Device (CCD) Camera as the primary fine focus sensor. Images of the thruster absorber are taken by the camera to be analyzed.**

- **Develop algorithm (s) for determining focal spot position from image of thruster absorber and secondary concentrator to produce control commands for the main concentrator. Optimize control with respect to power or energy (temperature) transferred to the propellant gas.**

History of Solar Thermal Area

- Roots to 1956 with the work of Krafft Ericke's Solar Powered Spaceship. Double Concentrator
- EOS 1963 Single Concentrator
- 1970's -1980's Component studies and development.
  - Off axis paraboloid shape.
  - Rhenium Coil Cylindrical cavity.
- 1991 Castable thin films developed to make inflatable concentrators.
- 1990's Rigidized structures developed and tested.
- 1990's Ground deployment of inflatable structures.
- 1997 Successful testing of a 2X3 meter inflatable – ready for upscaling.
- 2000 Successful deployment of a 4X6 meter concentrator.
- 2002 Mandrel for 4X6 inflatable built.
- 2003 Moly based thruster tested AFRL.
- 2003 Mandrel for 4X6 undergoes final machining.

History and Previous work

- Solar concentration
  - Ground Based.
    - Non- imaging Compound Parabolic Concentrator
    - Imaging Concentrator
  - Space Based.
    - Rigid Concentrators (Paraboloid)
    - Inflatable concentrators (Paraboloid)

Solar Sensor Systems

- Cavities (Black Body)
- Photo Cells
- Photo Diodes
- Radiometer/Radiometric (Flux Gauge)
- Solar Tracker
- Pyrheliometer (NIP)
- Pyranometer
- Beam Characterization system
- Calorimeter

Focus Parameters

- The focal beam, of a real concentrator, is a distorted and spread Gaussian; since a non-imaging concentrator can have large aberrations and non-zero slope errors, the focal beam would not perform ideally.
- Maximum intensity is related to maximum temperature. However, this parameter is not enough to indicate when the focal maximum is above or below the absorber instead of having its focal maximum exactly on the absorber plane.
- The intensity on the absorber should be symmetric for an on focus condition and may be utilized for coarse positioning as the focal beam is coming onto the absorber.
- Output temperature of the propellant could also be used as a determinant for on focus condition.
- Control to 0.1 inch and 0.1 degree is the required control tolerances.

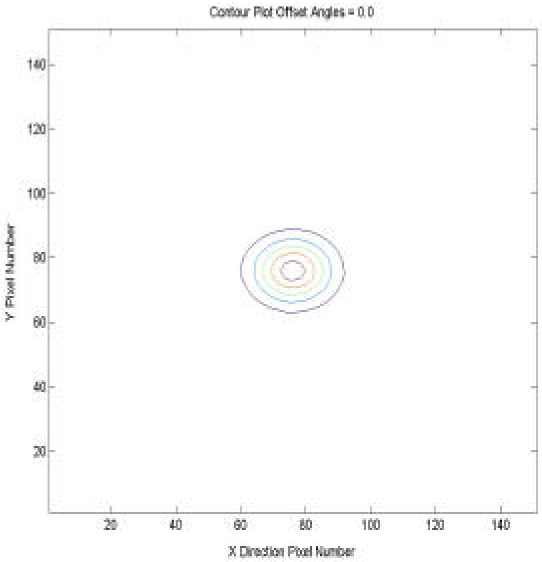
Available Equipment

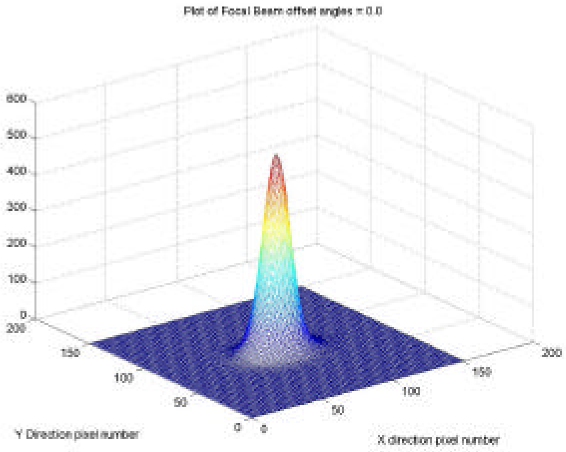
- 1 X 2 Elliptical Concentrator.
- CCD Cameras: SBIG ST 237 and ST 6.
- Matlab.
- Overhead projector.
- Lenses, baffles, pin-holes, optical table and other optical equipment.
- Incoherent light sources.
- Divergent sources.
- Sony Vaio Notebook Computer.
- Other Programming Languages.

Experiment # 1 Description

- **Utilize data from a computer program that simulated the focal spot image from an off-axis solar concentrator.**
  - **Data from the program was analyzed using the 2-D Fast Fourier Transform (FFT) to see whether the coordinate location of the maximum of the focal spot intensity could be obtained.**
  - **Data was also analyzed using a modified Short Time Fourier Transform (STFT) to see whether the coordinate location of the maximum of the focal spot intensity could be obtained.**

Experiment Description(cont)
Plots of Simulated Data

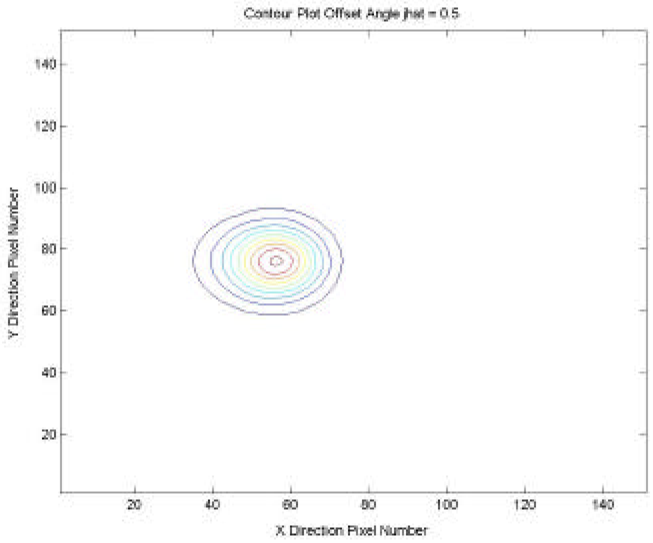


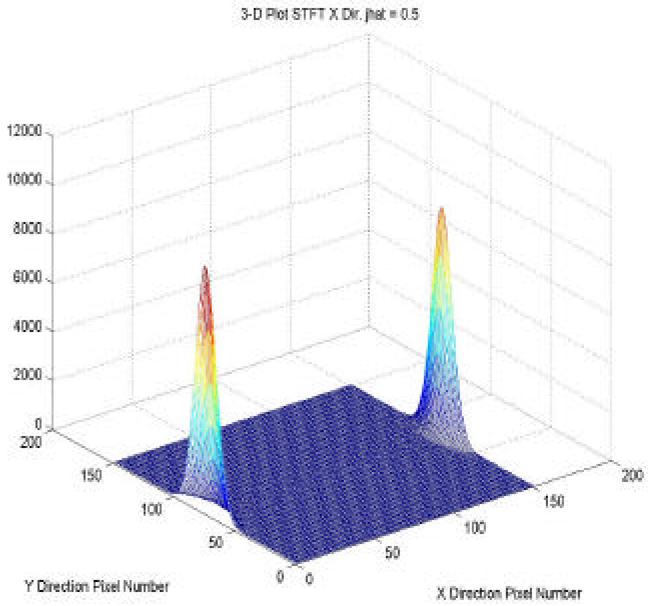


Results

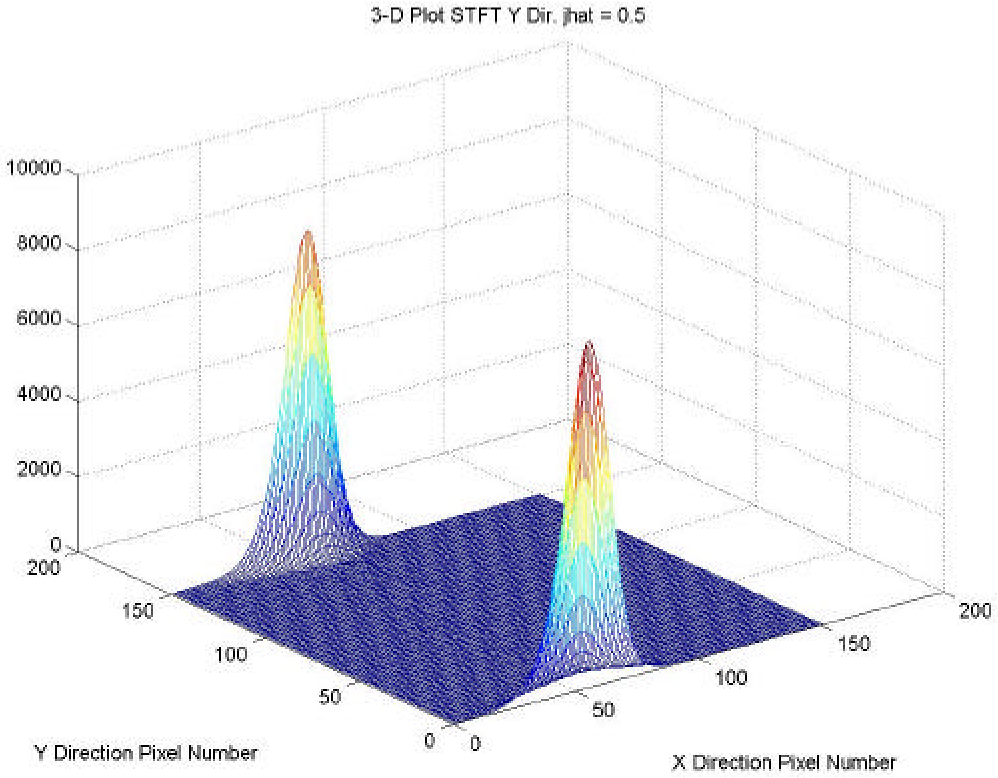
- **Results from 2 D FFT limited for providing X, Y location of maximum focal spot .**
- **Results from 2 D STFT provides the ability to find X, Y location data useful for generating command information to the concentrators.**
- **Results from 2 D STFT did not indicate when the focal spot beam just changed intensity (did not move in X, Y) as when the concentrator needed to move the focal beam closer to the target or away from the target.**

Plots STFT Data (Results)





Plots STFT Data (Results cont)



Conclusion and Future Work

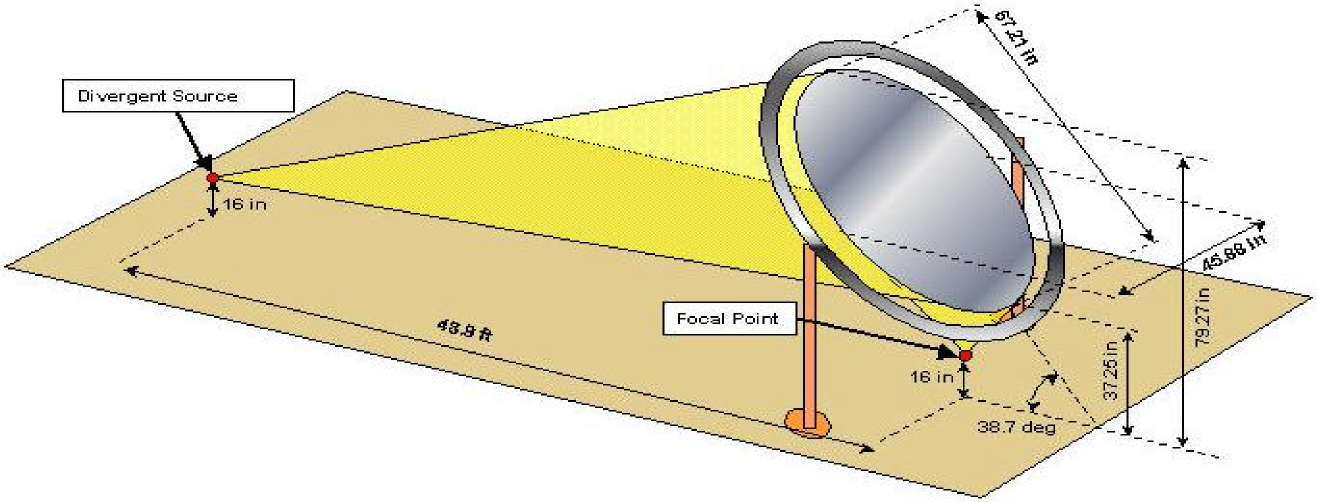
- STFT concept works in defining current location for the focal spot in X, Y.
- Could use maximum value found in each direction (X,Y) of the STFT to determine location for the focal spot.
- Need method to determine when focal spot energy changes and not (X,Y) location.
- Need to study “real” CCD pictures of absorber and secondary concentrator.
- Investigate other methods for focal spot location.
- Investigate pattern recognition methods in combination with wavelets for focal spot location.

Experiment # 2 Description

- **Charge Coupled Device (CCD) camera chosen as fine focus device for this research.**
- **SRS 1 X 2 meter elliptical concentrator used to form images on the thruster.**
- **Divergent light source used to provide simulated sunlight.**
- **SBIG ST-6 CCD camera used to obtain images.**
- **Scissors jack on block used to vary positions of the light source.**
- **Thruster images taken at 1 inch intervals in both vertical and horizontal locations using the 1m X 2m concentrator and a simulated sun light source**
- **Sony Vaio notebook computer used to take images.**
- **Matlab used for image enhancement and analysis.**

Experimental Setup

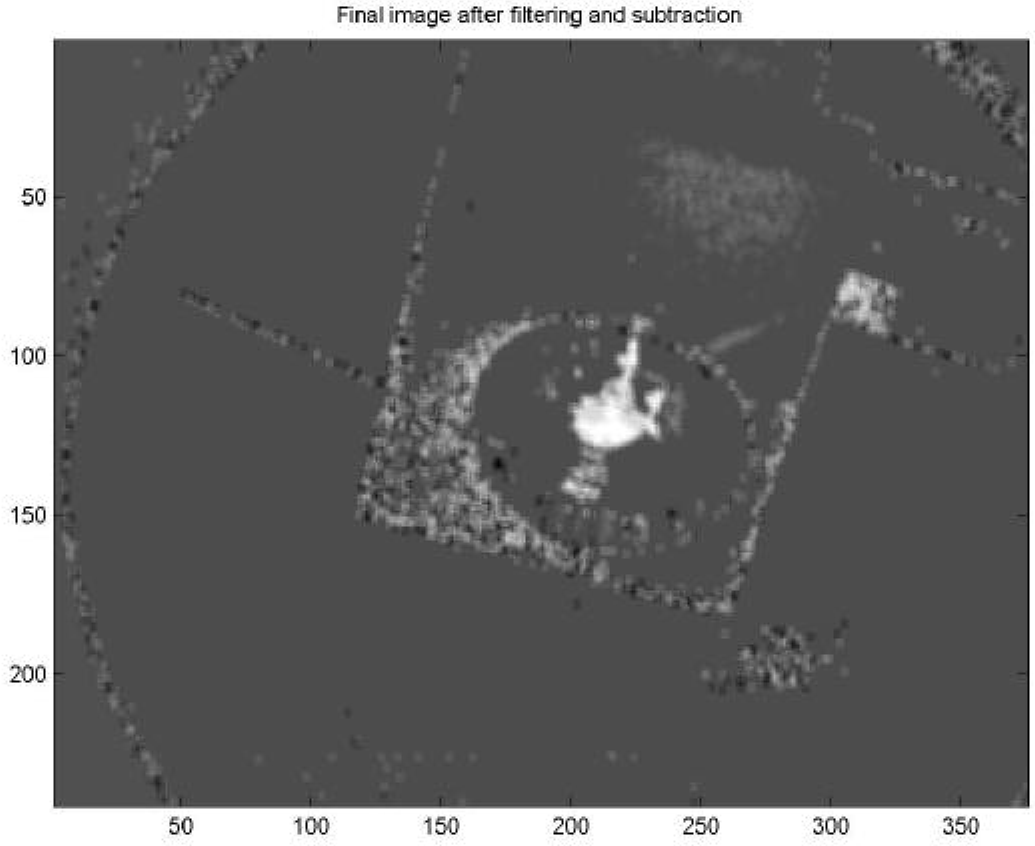
Test Apparatus



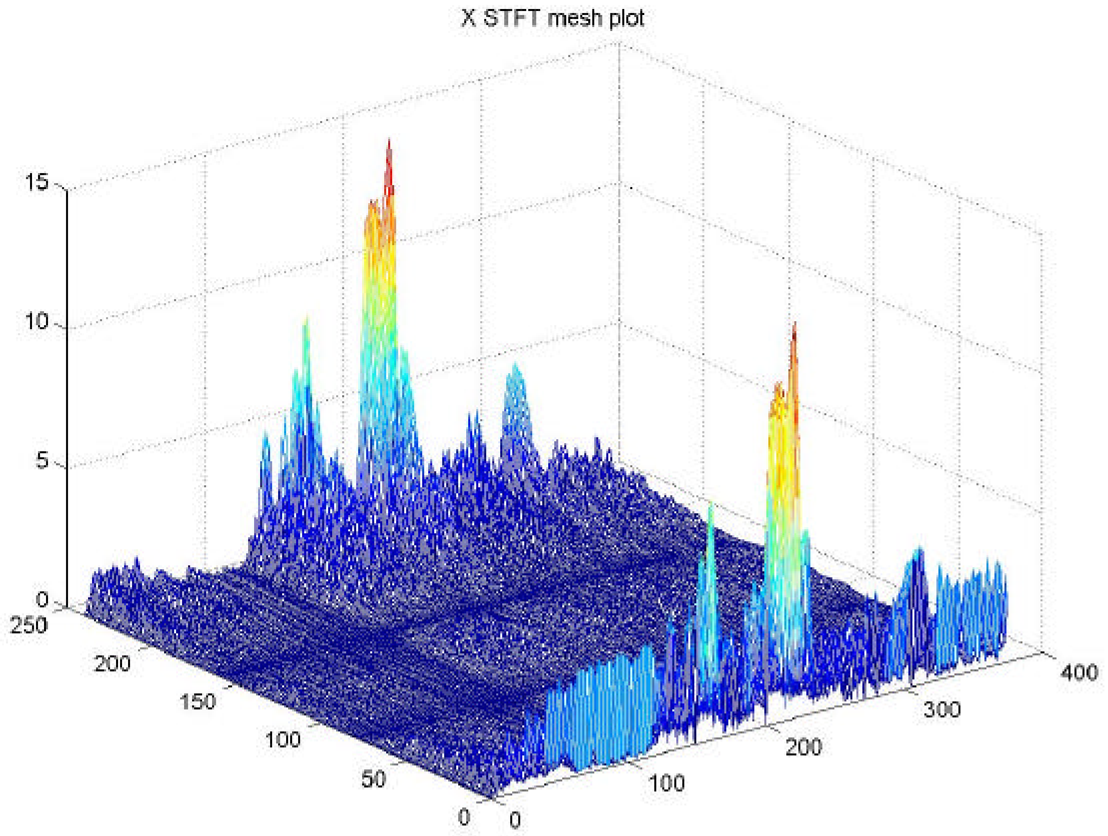
Results and Conclusions

- Histogram equalization of the images was necessary before final processing.
- Averaging filtering was the most useful filtering for using the STFT for determining focal spot location.
- Laplacian and Gaussian filtering was not useful for STFT, but may be useful for locating specular reflections using other methods.
- Images should be taken using a variety of exposures to ensure that the image histograms are more reasonably populated.

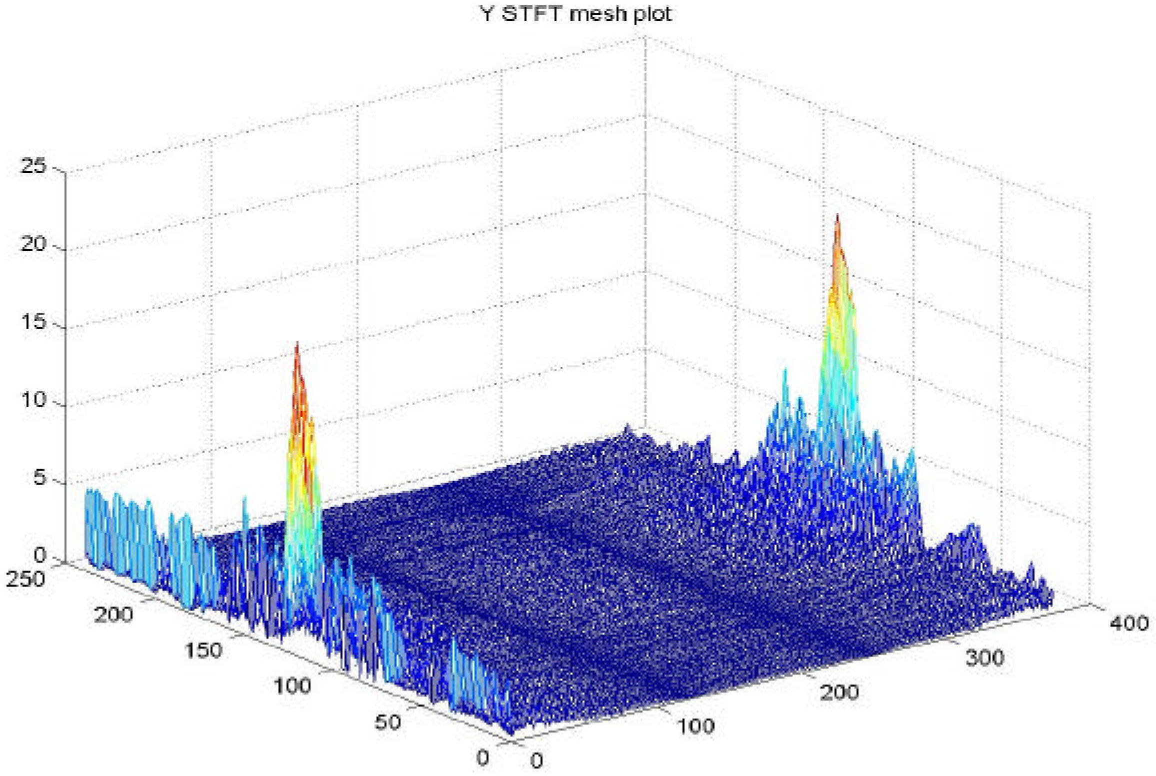
Average Final Image for Analysis



Thruster Image X STFT



Thruster Image Y STFT



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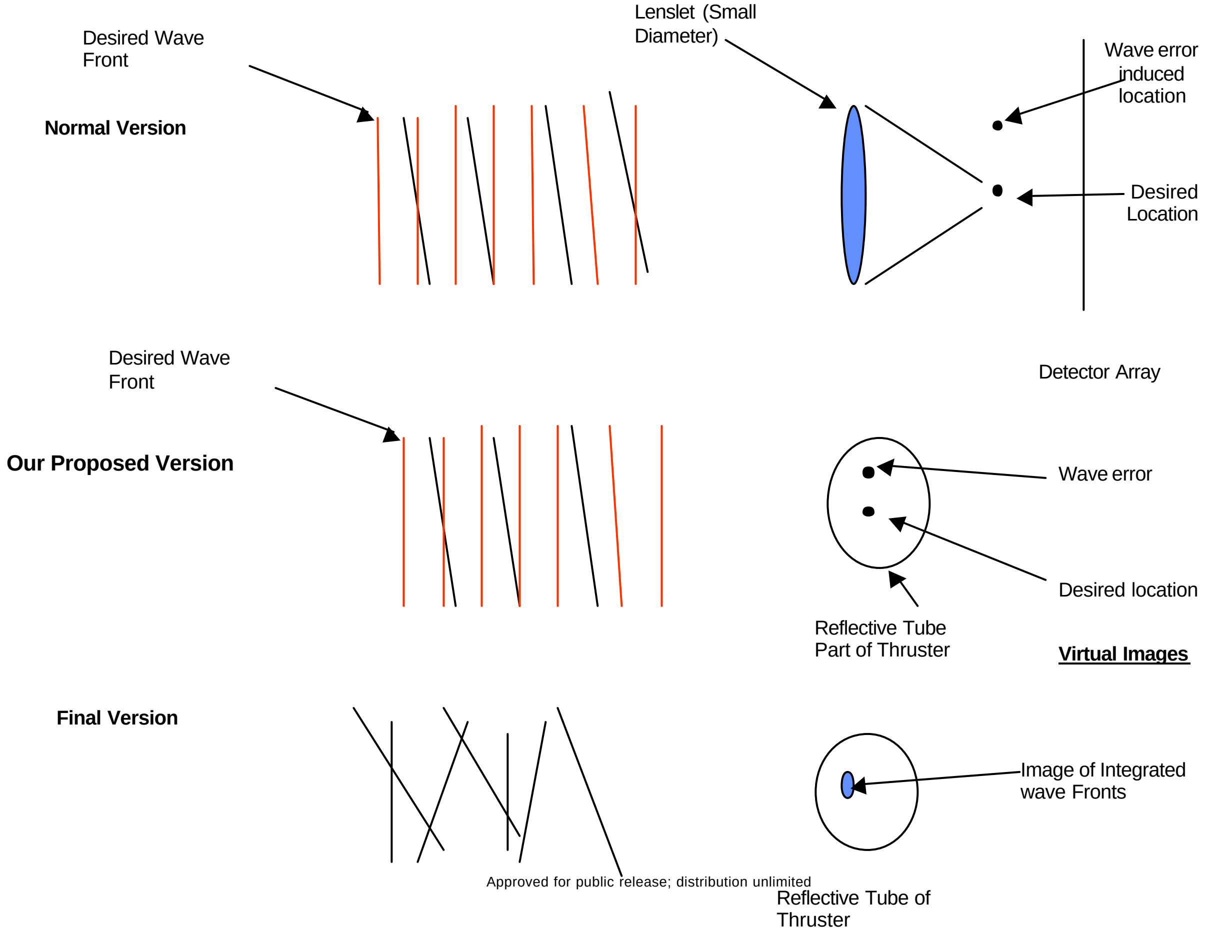
Conclusions and Future Work
Experiment 2

- **Work on separating specular reflections from diffuse reflections in order to accurately locate and track focal spot. This work would be above and beyond the frequency based work done up to this point. Could be frequency or spatially based or both.**
- **Work on developing a specular model for the reflectance function of the absorber/secondary concentrator, for use in determining specular-diffuse separation requirements.**
- **Work on algorithm to convert focal spot location errors to primary concentrator control commands.**
- **Work on real time hardware requirements for the control system.**

Wave Front Sensing

- **Hartmann Sensor**
  - **Utilized an array of holes or apertures to measure differences in tilt angle of waves by measuring the differences in position of the images of the apertures with a tilted waveform versus the images of the apertures with a non-tilted waveform. (Optical Path Difference OPD) A lens behind the aperture plate collects the information and directs that information to a collector array.**
- **Shack-Hartmann sensor**
  - **Replaced the array of apertures with small lenses or lenslets.**

Wave Front Sensing(Cont.)



Desired Wave Front

Normal Version

Lenslet (Small Diameter)

Wave error induced location

Desired Location

Detector Array

Desired Wave Front

Our Proposed Version

Wave error

Desired location

Reflective Tube Part of Thruster

<u>Virtual Images</u>

Final Version

Image of Integrated wave Fronts

Reflective Tube of Thruster

Reflection and Mirror Equations

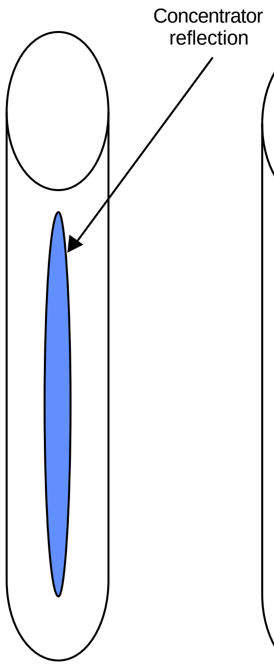
- Cylindrical mirrors are similar to convex spherical mirrors in one dimension.
- Cylindrical mirrors tend to elongate images along the axis of the cylinder surface, and reduce or squash the images along the radial surface.
- The mirror equations for convex mirrors are the same as for concave mirrors:

$$Hi = f*H0/D0$$

Where Hi is the image height, f is focal length, H0 is the height of the object and D0 is the distance from the object to the focus.

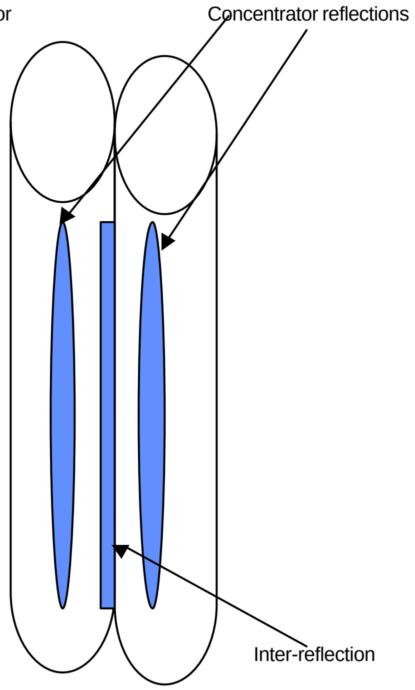
The equation for reflection is used to ray trace the images in the cylindrical mirror, since the cylindrical mirror is a more complex shape than a convex mirror. (Actually, a cylindrical mirror performs like a flat mirror in one direction and a spherical convex mirror in the perpendicular direction)

Cylindrical Mirror and Conical Absorber

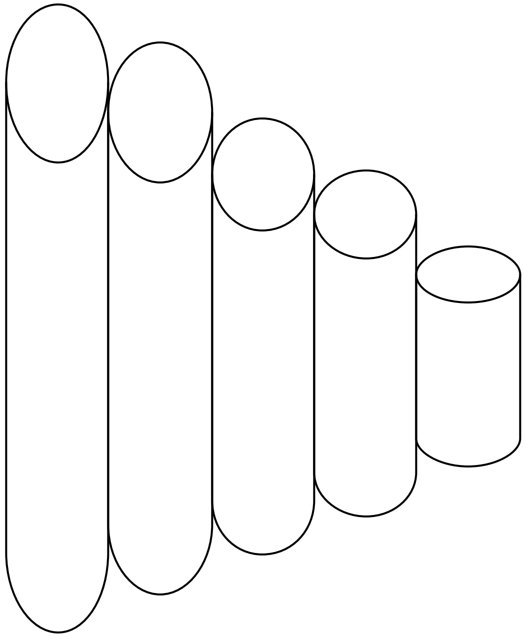


One Tube

“Cylindrical Mirror”



Two Tubes



Side View of Conical Absorber

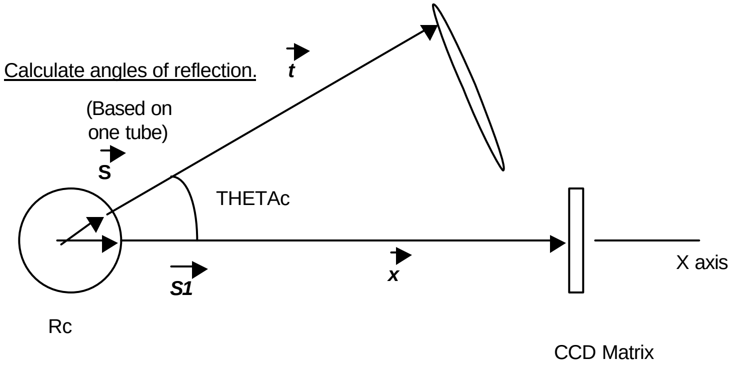
Front View of Conical Absorber

The tubing is used as curved cylindrical mirror surfaces.

For the on-focus situation each quadrant of the absorber will have an assumed symmetric image of the light from the concentrator.

<u>Calculate angles of reflection.</u>

(Based on one tube)



(vector equations)

$x = (S1 - Rc^{*}r)$

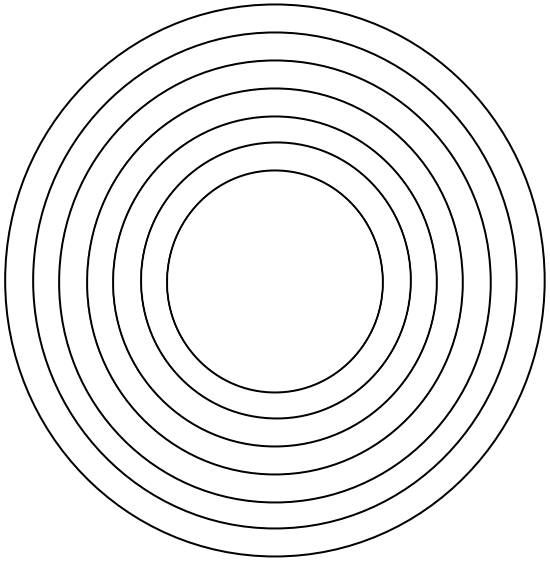
$t = (S - Rc^{*}r)$

r is the unit vector in cylindrical coordinates.

Center of tube is center of coordinates.

THETAc is the angle we are trying to find.

$X.r/|X| = t.r/|t|$

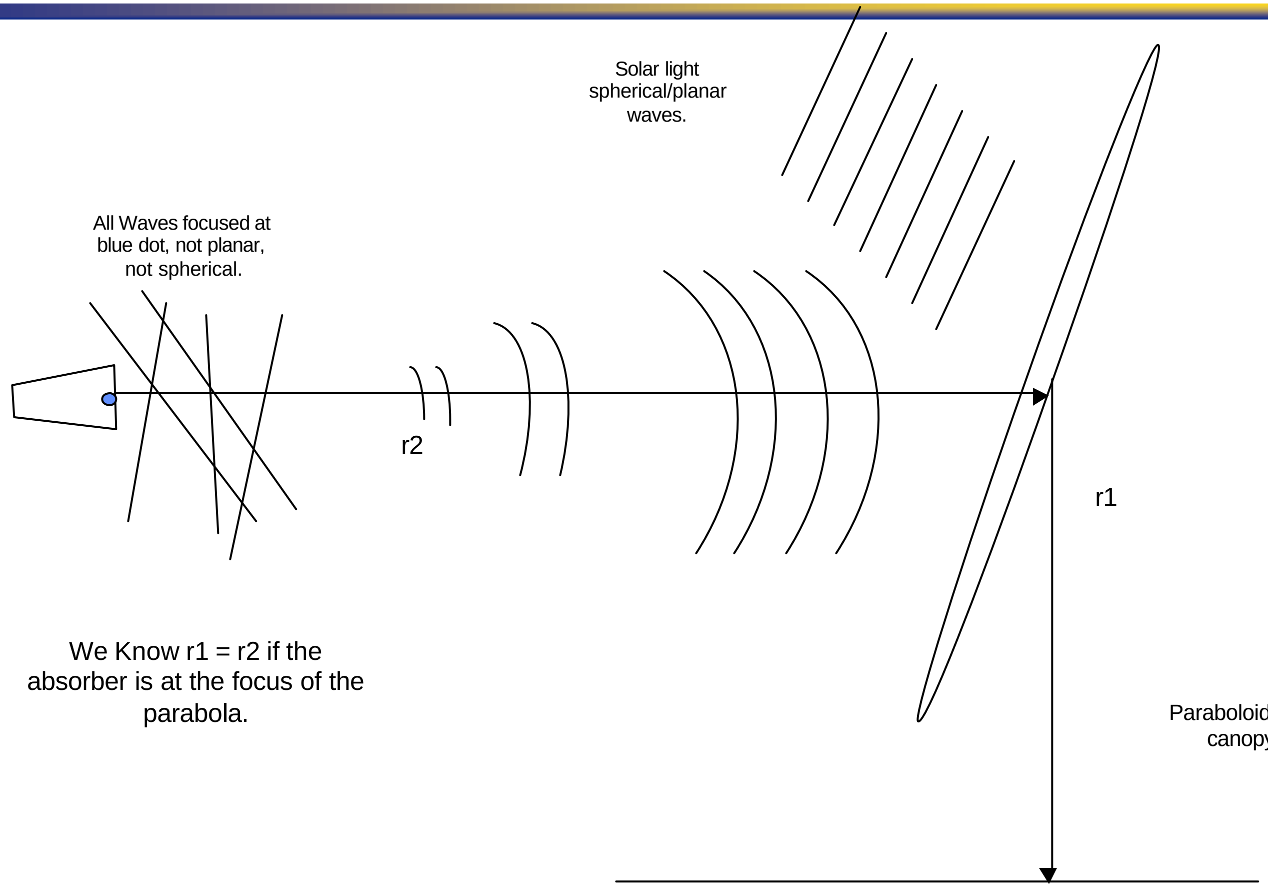


0.25 inch tubing used on the copper model

Focus Problem solutions

- Measure images of the concentrator in each tubular mirror. (Images would be much like that found in a cylindrical mirror, at least for a single tube. Most like a wave front sensor, with torroidal mirrors in multiple tube version)
- Calculate gradients (differences between areas) across and up and down images of tubes and compare to on focus levels. Assumed symmetry that occurs across the face of the absorber could be used as a rough estimate of on focus condition.
- Determine inter-tube reflection positions as a determination of focus level. (Least likely to have relevance, as preliminary analysis of images have determined.)
- Perturbation of focus, derive gradient.

Wave Fronts and Concentrator



Solar light
spherical/planar
waves.

All Waves focused at
blue dot, not planar,
not spherical.

r2

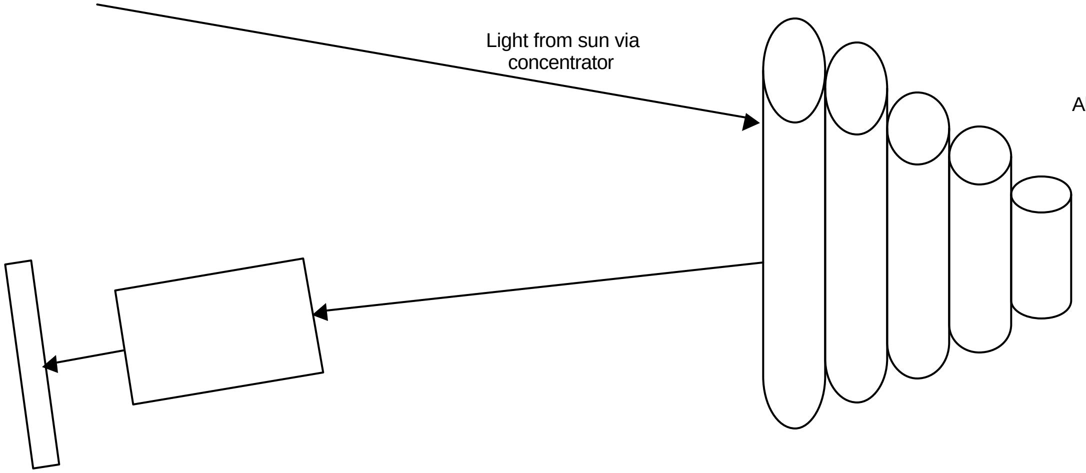
r1

Paraboloid with
canopy

Directrix

We Know r1 = r2 if the
absorber is at the focus of the
parabola.

Schematic of Proposed Solution



Light from sun via concentrator

Absorber side view

Optics Lens, etc

CCD Array

<u>FOV Calculate</u>

Lens: f = 100 mm

Pixel in camera : 7.4 um

Distance from lens to absorber: 1 m

One pixel then covers:
(1000/100)*7.4um = 0.074 mm

So that the FOV is equal to:

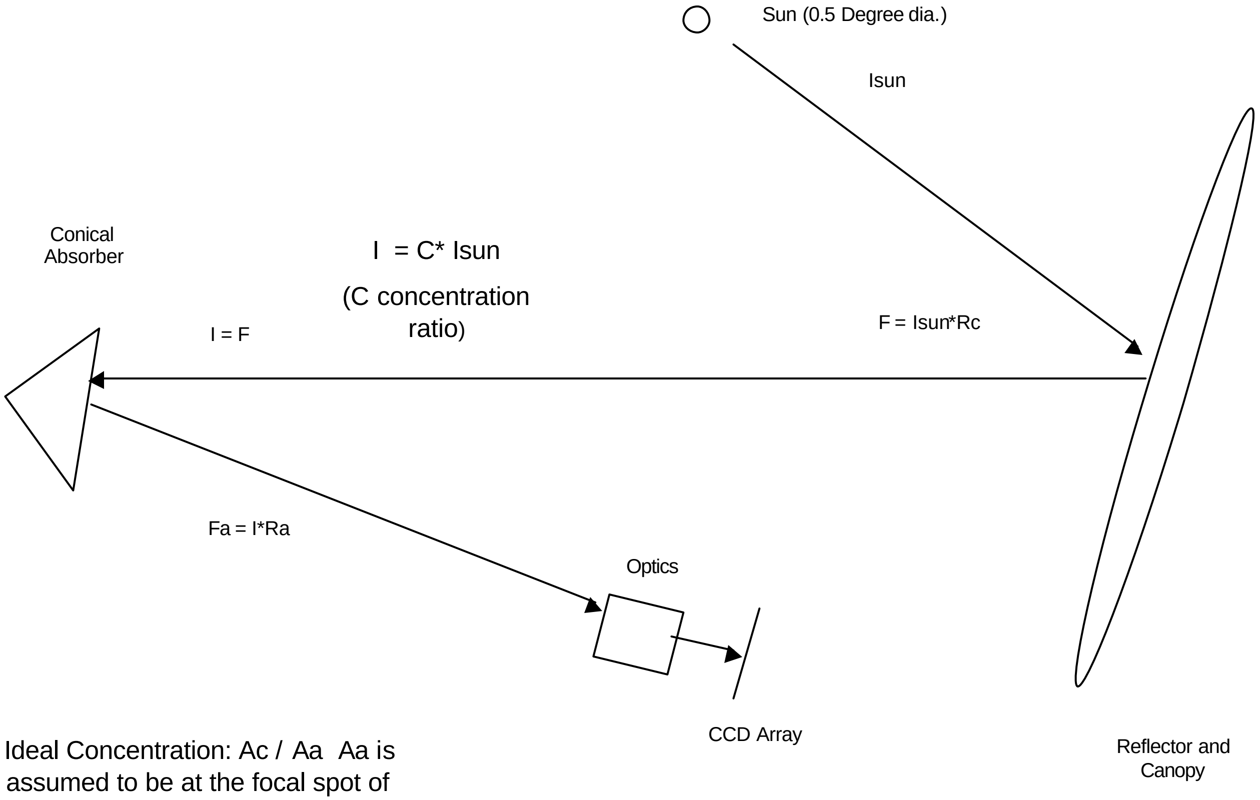
H: 657 * 0.074 = 48.62 mm (2 inch)

V: 495 * 0.074 = 36.63 (1.4 inch)

Algorithms

- **Each image taken would be processed by utilizing profile information along diagonal lines representing the four quadrants of the circle. (along the 45 degree angles, say)**
- **The areas of maximum intensity would be determined along each profile line. The maximums should occur roughly where the tubes appear in the image as they act like cylindrical mirrors. The difference or gradient between these areas should give an indication of the direction to the focal spot. (Almost a centroiding operation on the maximum areas in the image)**
- **By knowing where the center of the absorber is located with respect to the camera (a non-trivial assumption as the camera would probably be mounted on one of the concentrator's movable strut) , the computer should be able to generate x, y, z, roll, pitch, and yaw commands for the hexapod controller to move the concentrator to a new position to provide better focus and thus better heating.**

Intensity Schematic (Off Axis Paraboloid)



Sun (0.5 Degree dia.)

Isun

Conical Absorber

I = C* Isun

(C concentration ratio)

I = F

F = Isun*Rc

Fa = I*Ra

Optics

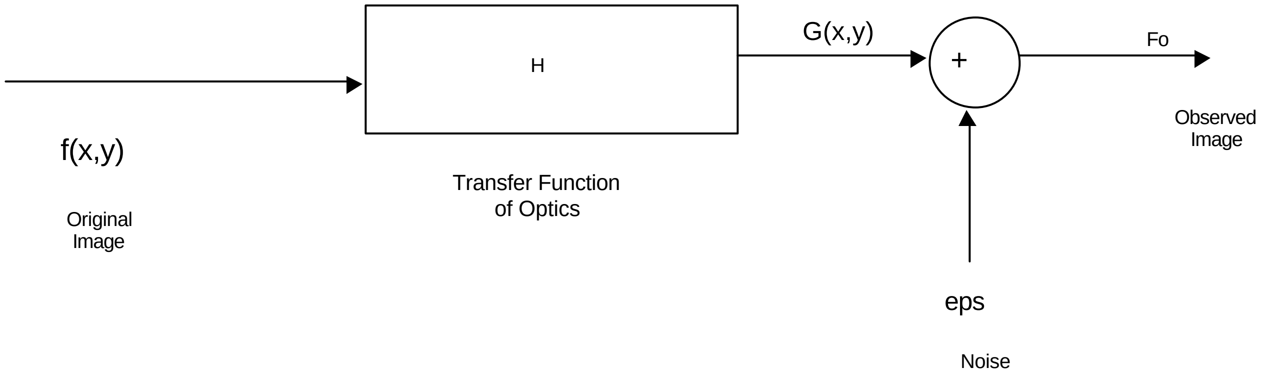
CCD Array

Reflector and Canopy

Ideal Concentration: Ac / Aa Aa is assumed to be at the focal spot of the concentrator.

Ideal ratio is 46000:1

Control System Block Diagram (Power Calculation)



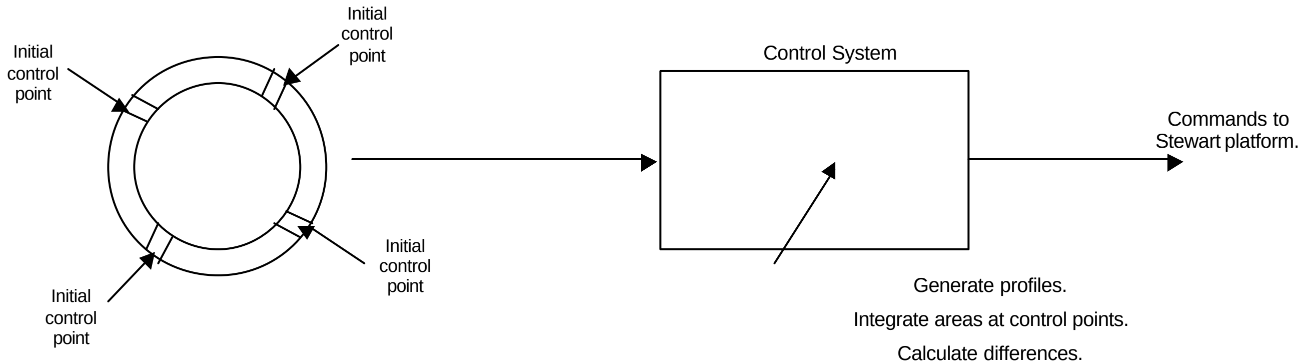


Image of outer ring only.

Generate profiles.

Integrate areas at control points.

Calculate differences.

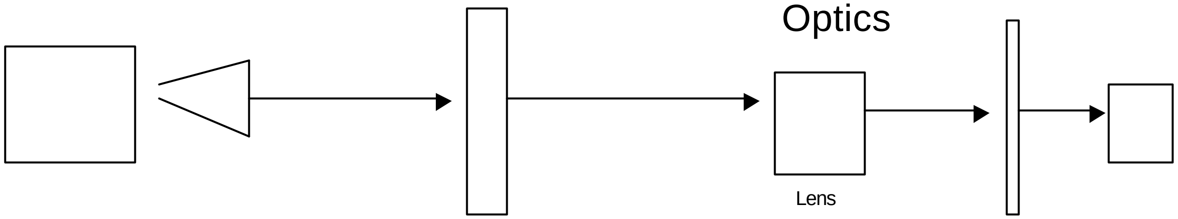
Determine center of the differences to locate focal beam.

Determine x, y, z, roll, pitch, yaw cpmmands.

Modeling and Simulation

- Concentrator Model
  - Off-axis
  - Software
- Sensor Model
  - Cylindrical Mirrors
  - Copper cooled tube conical absorber
- Light intensity or power model
- Noise Model

Noise Schematic



Mechanical

Absorber/Sensor

Vibration

Specular/Diffuse

Heating effects

Window
(Testing Only)

Refraction

Snell's law

Optics

Lens

Aperture
Position and
Size

CCD and
Electronics

Photon Noise

Read Noise

Dark Noise

System Noise: contamination
from out-gassing.

What I learn slide.

- Apply a modified old technique to a new situation. Wave front sensor.
- Learn to analyze non-imaging concentrators to determine how to point them for maximum power transfer.
- Image Analysis. Using images to determine parameters to be used to control concentrators. Calculating focus parameters from the images of the absorber using a technique similar to finding the centroids from a wave front sensor and we are looking at all of the waves coming to the absorber not just a particular wave. In the case of this research, the wave front sensor is the absorber and it is collecting all of the waves of light from the concentrator. The tubes in the absorber replace apertures or lenslets of the Shack-Hartmann or Hartmann sensor. So instead of determining a centroid for light passed through apertures, the mirrors reflect the light from the concentrator back to the CCD. Each tube reflects an image of the concentrator to the CCD. When the concentrator is focused, the intensity of the light reflected should be approximately uniformly distributed throughout the absorber. If a difference is found in each of the four control points, the misalignment is determined by calculating the centroid of the integration of intensity at each tube. The difference along each of the control point profiles determines where the focus is located and provides the direction of travel needed to force the focus back to the center.
- Utilize Digital Signal Processing and Detection and Estimation analysis in a different area.
- Solve an unusual problem using a combination of old skills and new ideas.

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