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CfAO Adaptive Optics Summer School, August 9-14, 2009

Inquiry Lesson Plan

Fourier Optics Lab

Audience: Participants enrolled in the CfAO Adaptive Optics Summer School

Number of participants: 63 **Time:** Three hours

Required staff: 3 facilitators

1 Overview

a Lab Description

The Fourier Optics Lab is a three-hour laboratory activity to acquaint participants with some of the fundamental qualitative principles of wave optics. The lab also gives practical hands-on experience with simple optical systems. To expose each group to a greater number of phenomena relating to Fourier Optics, each group also has several opportunities to discuss their observations and challenges with other participants.

This document contains all materials necessary to plan and execute the laboratory activity, including this lesson plan, a schedule, materials list, and other necessary components. See the Table of Contents for a full list.

b Lab Facilitation

This lab activity is designed as a "scientific inquiry" activity in which participants choose the focus of investigation from a constrained set of student-generated topics. The inquiry design more fully engages the interest of the participants and allows them a greater sense of ownership in the process. The challenge of this pedagogical method is the need for greater instructional oversight and greater manpower – the maximum span of control in this lab is probably three groups, or about nine students, per instructor. The inquiry model also encourages instructors to eschew direct instruction in favor of a more subtle "facilitation" of the learning process.

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c Objectives

i Content Goals

Goal	Evidence
Particpants construct and explain an optical diagram that demonstrates the function of each component in their setup	The correct drawing or explanation
Participants understand the connection between wavefront errors/aberrations and Shack-Hartmann spot locations/movements	A correct diagram/oral explanation
Participants understand that wavefront errors/aberrations redistribute PSF core intensity into speckles outside the core	A correct diagram/oral explanation
Participants understand the relationship between PSF (resolution and shape) and (aperture size and shape)	A correct diagram/oral explanation Participants explores high-contrast phenomena by varying aperture size/shape
Participants exhibit proper lab safety procedures and equipment treatment	
Participants understand the difference between the image/focal plane and the pupil plane	Participants correctly use the terms in conversation with each other, with facilitator, or during the presentation
Participants understand that phase errors introduced in different planes have different effects.	A qualitatively correct diagram/oral explanation

ii Process Goals

Goal	Evidence
Participants will collaborate and work as effective members of a team	Participants talk to one another Participants explain coherently to each other, or to facilitators, what their group discovered/accomplished Are open to opinions of team members
Participants are able to accurately depict or record their observations	
Participants appreciate the necessity of, and demonstrate and maintain, a properly calibrated apparatus.	E.g., image or spots are properly focused Participants mention/discuss calibration/alignment
Participants define an investigable, directed	

question or problem
Participants stay on task

iii Attitudinal Goals

Goal	Evidence
Participants develop a stronger connection to/with the Adaptive Optics community	Frank, open discussion between groups and group members

iv CfAO Program Goals

Students should draw on prior knowledge.

Students should be able to observe and communicate.

Students should gain experience for jobs/careers.

Students should make predictions about phenomena

d Schedule: Three lab sections, each three hours

i Session 1: 1:45-3:15 or 8:45-10:15

Task	Duration (min)	Time (Lab 1 & 3)	Time (Lab 2)	Facilitator
Introduction to Fourier Optics Lab, staff, inquiry process, starters, lab procedures	7	1:45-1:52	8:45-8:52	Ian
Starter activities (3 stations, rotating) + investigation topic generation	18	1:52-2:10	8:52-9:10	All
Topic categorization and group formation	8	2:10-2:18	9:10-9:18	Sylvana
Investigation I introduction	2	2:18-2:20	9:18-9:20	Sylvana
Investigation I	50	2:20-3:10	9:20-10:10	All
Share with other group	5	3:10-3:15	10:10-10:15	All

ii Break: 3:15-3:45 or 10:15-10:45

iii Session 2: 3:45-5:15 or 10:45-12:15

Task	Duration (min)	Time (Lab 1 & 3)	Time (Lab 2)	Facilitator
Thinking tool + Investigation II introduction	3	3:45-3:48	10:45-10:48	Tuan
Investigation II	47	3:48-4:35	10:48-11:35	All
Prepare for sharing	8	4:35-4:43	11:35-11:43	All
Group sharing	22	4:43-5:05	11:43-12:05	Ian
Synthesis discussion	10	5:05-5:15	12:05-12:15	Tuan

<u>Homework:</u> *Feedback form*

2 Full Activity Description

a Introduction

Time: 7 min.
Facilitator: Ian
Grouping: Entire class
Materials:

- Fourier Optics Guidelines handout
- First-half schedule at front of room

Set-up:

1. Stools are only around the six starter stations
2. Lasers off
3. Have starter stations set up.
4. Investigation topic categories (for group formation) already up at the front of the room

Strategy:

1. As students come in, suggest they sit with new people and don't touch the optics
2. Introduce:
    1. Facilitators.
        1. “I'm Alex, this is Jordan. We designed the activity you're about to do, so we'll be very interested to hear your feedback at the end of this. We're also here to guide you through the lab activity and to make sure that your time here is productive and well-spent.”
    2. Inquiry process & role of facilitators
    3. Fourier Optics ~2 min
        1. “You're familiar with Ray, or Geometric, Optics – the idea that light travels in straight lines. Fourier Optics describes a range of phenomena that cannot be described by light traveling in straight lines. It deals with light acting as a physical wave that can interfere with itself. The goal of this lab is to give you a qualitative familiarity with the phenomena that result from this wave behavior of light.”
    4. Today's schedule (on board)
    5. Lab procedures:
        1. “You'll be working with the optical benches set up in front of you. Generally, use common sense.”
        2. “Keep your eye above the level of the laser beams, and follow the beam with a white card rather than with your hand – otherwise a hand inevitably tracks a beam right onto a lens, getting fingerprints all over it.”
        3. “Also be careful when adjusting the size of the iris: when it starts to resist, don't force it any further! Otherwise it'll break completely.”
    6. Starter stations -- remind students not to reset optics' locations yet
3. "What questions do you have so far?"
4. Disperse & begin starters

b “Starter” activities

18 min. (Tuan, Ian, Sylvana)

1 All three starters are done in parallel, rotating every 6 minutes.
2 Facilitator demos the Starter for **2 minutes only** at one of the starter setups

3 For the first starter **only**, discuss the optical setup BRIEFLY:
   a. "The laser generates a plane wave analogous to the light from a distant object or star."
   b. "The iris, which determines the size of the aperture and how much light gets through, is analogous to the pupil in your eye or to the primary mirror of a telescope."
4 Don't:
   a. "give it away" by telling students what to see at each starter!
   b. use jargon any more than necessary (e.g., "fuzzy" instead of "apodized")
5 For later groups, it's okay to allude to phenomena they've already seen
6 Participants may be reluctant to write questions/observations: lean on them heavily!
7 Someone (Sylvana) will direct students to rotate at the end of each six-minute activity

i Starter 1: Aperture Shape and PSFs

Facilitator: Ian
Grouping: one-third of class
Materials: At each station:

- Cardstock with pre-cut aperture shapes of comparable size:
  (circle, ellipse, square, triangle, hexagon, hourglass...)
- Printed transparency, with aperture shapes of comparable size:
  (circle, ellipse, square, triangle, hexagon, hourglass...),
  both hard-edged and apodized

Set-up:

1 Two optical benches, set up to view the PSF formed by the iris pupil (open ~2 mm)
2 Cut and printed aperture cards at both stations
3 Notecards spread out around stations
4 No IDL software yet (not enough time)

Strategy:

1 Gather two groups of people around one optical bench & computer
2 Describe that:
   a. we're seeing the PSF formed from a circular aperture
   b. the next five minutes are to investigate the effect of aperture shape on the PSF structure, and that we'll look at a number of aperture shapes of comparable size
   c. participants should write down any questions they have about what they're seeing (and why)
1 Show a circular aperture, then a hemicircle in 2 orientations (by aperture blocking with a card)
2 Show a square, then a hexagon, then hard-edged and apodized printed squares
3 Remind particpants to write down questions and keep them close, then split group across both stations

ii Starter 2: Aperture Size and Resolution

Facilitator: Sylvana
Grouping: one-third of class
Materials: At both stations:

- Cardstock with several pairs of pinholes of varying separation

Set-up:

1 Two optical benches at the front of the room, set up to view the PSF formed by the iris pupil (open ~2 mm)
2 Cards with pre-punched holes at both stations
3 Notecards spread out around stations
4 No IDL software yet (not enough time)

Strategy:

1 Gather two groups of people around one optical bench & computer
2 Describe that:
   a. we're seeing the PSF formed from a circular aperture about 2 mm across; in this setup, the circular iris aperture is analagous to a circular telescope mirror
   b. the next five minutes are to investigate the effect of aperture size on the PSF structure, and that we'll look at a number of (circular) aperture sizes and arrays
   c. participants should write down any questions they have about what they're seeing (and why)

1 Stop down the iris slightly, note that the PSF is changing.
2 Open up the iris, and note what happens now. Repeat once, if necessary.
3 Insert a notecard with a single pinhole into the beam, and note the resolution now
4 Open the iris sufficiently to illuminate two pinholes, and note the fringe pattern that results
5 Indicate to both groups that they have pushpins and cards to make their own sets of holes
6 Remind participants to write down questions and keep them close, then split group across both stations
7 At the end of the last starter, Sylvana gets ready for the group formation

iii Starter 3: Phase Errors

Facilitator: Tuan
Grouping: one-third of class
Materials: At both stations:

- Cellophane plastic wrap/ziploc bag
- Blank transparency
- Clear plastic CD cover
- Various small, cheap lenses with various aberrations

Set-up:

1 Two optical benches, set up to view the PSF formed by the iris pupil (open ~2 mm)
2 Aberrator sets at both stations
3 Notecards spread out around stations
4 No IDL software yet (not enough time)

Strategy:

1 Gather two groups of people around one optical bench & computer
2 Describe that:
   a. we're seeing the PSF formed from a circular aperture about 2 mm across
   b. the next five minutes are to investigate the effect of wavefront aberrations on the PSF structure, and that we'll look at a number of aberration effects
   c. participants should write down any questions they have about what they're seeing (and why)

1 Insert a plastic bag across the aperture, and have them note the speckle pattern that results

2 Insert the CD cover across the aperture, and note how the speckles are different
3 Insert the blank transparency, and slide is slowly across the aperture; note how the speckles react
4 Use low-, hi-astigmatic lenses, and defocusing lenses
5 Change size of aperture to show speckle size relation
6 Indicate to both groups that they have several sets of aberrators, as well as the optical lenses to introduce known aberrations (focus, astigmatism, etc.)
7 Remind participants to write down questions and keep them close, then split group across both stations

c Group Formation & Investigation I Introduction

Time: 10 min
Facilitator: Sylvana moderating, Ian writing questions
Grouping: Entire class
Materials:

- Prepared “topic categories” written and widely spaced at the front of the room

Set-up:

1 Write/tape 'topic categories' up around front of the room

Strategy:

1 “We're about to begin a fifty-minute focused investigation of one particular aspect of Fourier Optics. You may or may not choose a question that you originally came up with - maybe there's another question that you didn't think of but that you find interesting. You'll then get yourselves into groups based on the questions or topic you're interested in. If you can't formulate a question, you can just mention something you noticed and thought was interesting. Please don't try to answer other people's questions during this time.”
2 One facilitator asks for questions that came up during the starter activities, and another facilitator groups these responses on the board.
   a. For questions we can't/don't want to address: “That's a very good question, but it's not something we're equipped to study in detail here in this lab.”
3 Once sufficient questions have been raised, tell students:
   a. 'These questions tend to fall into a few main categories, corresponding to the startup activities you did. Pick a question that you especially want to investigate, and in a moment, go to the starter station corresponding to that topic's general category. If you're interested in trying something that you don't think matches any of these categories, go to the seventh table in the back and come up with a mutually agreeable question to investigate there. Whatever you pick, you won't be restricted to just this one topic or question.'
   b. 'Once you've moved, form yourself into a group of **three** people; there should be seven groups. Sit down with your group at an optical bench, but don't start quite yet”
   c. In addition to the materials in front of you, there is a table full of various supplies up at the front of the room that you may want to check out. If you want something else, talk to your facilitator and they'll see what they can do for you.”
   d. “Remember that you also have a handout in your Summer School packet describing some of the software and equipment in front of you.”

d Investigation I

Time: 50 min
Facilitator: All (timekeeping and group formation: Ian)
Grouping: Seven groups of 2-3 participants each
Materials:

- All starter materials:
- Notecards, pins, razor blades, aberrators, etc.
- Computers running IDL Fourier Optics demo & camera software
- Optical benches
- NO lenslet arrays

Set-up:

1. Supplies at the front of the lab room:
2. At each workspace a computer and optical bench
3. Ian has three groups, Tuan and Sylvana each have two

Strategy:

1 Schedule:
  - a. Introduce yourself to each group; note/jot down their names, and explain facilitation.
  - b. By 10 minutes in, each group should have a firm, explicit investigation goal
  - c. With 20 minutes left: Decide which groups will pair up to discuss their progress
  - d. With 10 minutes left:
    - i. Encourage groups to begin wrapping up
    - ii. Explain that each participant will briefly discuss what they've found/done with members of other groups
    - iii. **If groups are still floundering, start facilitating in a more heavy-handed, directive manner**

1 "Toolbox":
  - a. When possible, avoid answering direct questions: ask further questions to motivate participants to answer them themselves.
  - b. Gauge groups' and individuals' skill levels: beginning groups need more facilitation, and beginning students should be more active 'do-ers'
  - c. If one student 'gets it' but others don't, get them to explain to their group members
  - d. If you see someone else's group struggling, let their facilitator know!
  - e. Depending on a group's topic and progress, remind them of additional relevant materials as necessary – e.g., IDL Fourier Optics demo or lens kits
  - f. Fundamental questions for beginning or struggling groups:
    - i. "How do we define resolution in a meaningful way?"
    - ii. "what do each of these components do?"
    - iii. Why is a second lens necessary?
    - iv. Suggest they make a drawing (of the optical setup, of the aperture, of a PSF...)
    - v. Suggest they image the pupil (to visualize aberrations, to examine shapes...)
  - g. Medium-level questions to ask groups:
    - i. When you see a PSF, are you looking at the near or far field?
    - ii.
  - h. Advanced topics for groups that really 'get it':
    - i. How do apodized pupils work?

    ii. What is non-redundant aperture masking? Create one to investigate how it works.
  i. Any question relating to Lab Goals are also fair game!

e Share with other group

Time: 5 min
Facilitator: All
Grouping: Three discussion groups, composed of two-three investigation groups each
Materials:

- None

Set-up:

1. As decided previously during the investigation, each group goes to one of three groups at the front, middle, or rear of the lab room

Strategy:

1. Tell the students:
   a. You have about 5 minutes to discuss with one or two other groups about what they've investigated thus far, what questions came up during the inquiry, anything interesting they learned, or something you're still puzzled about, etc...
   b. May also discuss further possible avenues of exploration for the next session.
   c. Feel free to continue these discussions during break, and be back in half an hour!
2. Facilitators may have to ask questions as well to stimulate participants to speak
3. After 5 minutes, tell students: “You're now officially on break. Feel free to keep your discussions going while you go to get some coffee or cookies. Just be sure to be back in 30 minutes!”

f Break

Time: 30 min
Facilitator: All
Strategy:

1. Facilitators confer and brainstorm on current progress/difficulties/next steps
2. Determine focus of 'thinking tool' that will help the greatest number of groups
3. Get coffee, if necessary

g Thinking Tool & Investigation II Introduction

Time: 3 min
Facilitator: Tuan
Grouping: Entire class
Materials:

- Schedule for the second half, up at the front of the room

Set-up:

1. None?

Strategy:

1 Thin Lens equation: remind class about the basic equation in ray optics and suggests that it may help in their investigation as they start thinking about imaging things.
   a. Other options here, depending on what students have struggled most with:
      i. Shack-Hartmann wavefront sensor demo/discussion
      ii. Given an irregular polygonal aperture, predict and test the PSF shape
2 Remind participants they can continue their first investigation, but we prefer them to investigate a second phenomenon – including anything with lenselet arrays, if desired.
3 Remind them that at the end, each group member will conduct an individual presentation on one of the group's two investigations. Explicate our goals for this sharing (gain experience presenting findings, share results about different phenomena with rest of the group, ...)
4 Mention that lenslet arrays are also now available
5 Show schedule for second half of the lab (on slides, board, or poster paper)

h Investigation II

Time: 47 min
Facilitator: All
Grouping: 7 groups of 2-3 participants each
Materials:
- Same as Investigation I, w/addition of lenslet arrays

Set-up:
1 Continuing on from previous session

Strategy:
1 Schedule:
   a. Initially give groups a bit of time to decide on their inquiry focus
   b. By 10 minutes in, each group should have a firm, explicit investigation goal
   c. With 15 minutes left:
      i. **If groups are still floundering, start facilitating in a more heavy-handed, directive manner**
      ii. Encourage groups to finish up
      iii. Explain that each group will make a poster and present what they've found/done
   d. As groups finish up, direct them to the poster/presentation materials. They can also make printouts using the next-door printer and a USB flash drive
1 "Toolbox":
   a. When possible, avoid answering direct questions: ask further questions to motivate participants to answer them themselves.
   b. Gauge groups' and individuals' skill levels: beginning groups need more facilitation, and beginning students should be more active 'do-ers'
   c. If one student 'gets it' but others don't, get them to explain to their group members
   d. If you see someone else's group struggling, let their facilitator know!
   e. Depending on a group's topic and progress, remind them of additional relevant materials as necessary – e.g., IDL Fourier Optics demo or lens kits
   f. New questions to pose with a Shack-Hartmann sensor:
      i. How do various phase errors affect spot shapes/locations?
      ii. How does the SH WFS measure aberrations?
      iii. Any question relating to Lab Goals are fair game!

i Prepare for Sharing

Time: 8 min
Facilitator: All
Grouping: 7 groups of 2-3 participants each
Materials:

- Printer w/paper
- Large poster paper
- Markers

Strategy:

1. Direct groups to the materials, and instruct them how to print
2. Tell them to begin preparing a poster to present their findings to the rest of the lab members

j Sharing

Time: 22 min
Facilitator: Ian
Grouping: Entire class (in investigation groups)

Materials:

- Large red construction paper
- Rubric forms

Strategy:

1. Give general instructions:
    a. Remind everyone that everyone from each group should contribute and speak
    b. Remind people to state their names
    c. Each group gets 1 minute per person for each member to discuss their group's difficulties, discoveries, and their explanation
    d. Write down any questions that you have to discuss with the speakers after the lab
2. Correct any glaring mistakes or errors in presentations or on posters
3. Move posters to side of the room when done

k Synthesis Discussion

Time: 10 min
Facilitator: Tuan
Grouping: Entire class
Materials:

- None

Set-up:

1. Class comes back together

Strategy:

1. Sum up important topics and concepts (content and process goals):
    a. Relationship between pupil plane and the image plane (possibly something about near field vs far field if required). Give simple examples of Fourier transforms.
    b. Lenses do Fourier Transforms
    c. Larger apertures sample more spatial frequencies to increase resolution

d. Phase errors distort wavefronts in knowable ways
e. Discuss resolution and shaped pupils
f. Discuss phase errors if someone investigated them
g. Discuss how SH WFS works - what the positions of spots tell us about the wavefront.
h. Discuss high contrast imaging if groups tried to investigate.

2 Use specific examples from observed group investigations

3 Encourage participants to give us detailed feedback in person or on their lab evaluation forms

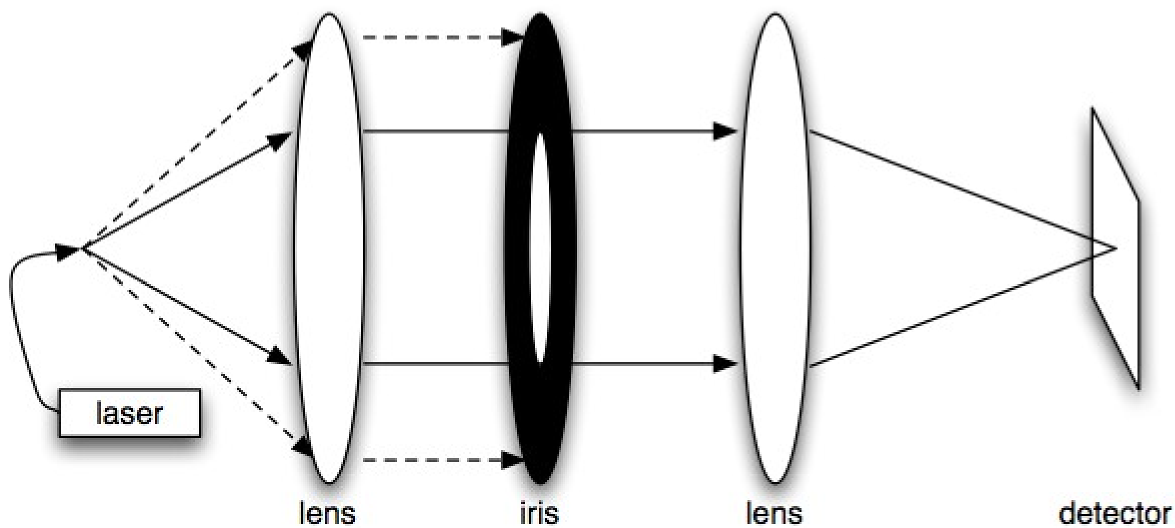
3 Appendices:

a Materials List

Item	Number	Obtain from:
Optical supplies:		
Shear plate	1 total	Lab for AO, UCSC
Optical bench supplies	7 sets	Lab for AO, UCSC
One 1-meter rail	1	
Rail brackets	6	
Post holders (2”)	6	
Posts & set screws (3”)	6	
Card clamp/holder	1	
Plane wave source (laser)	1	
CCD w/mount & ND filter	1	Newport SM1RC
Convex lenses w/mounts	2	
3-inch iris w/mount	1	
Lenslet array w/mount	1	1000-175 (array) and Newport LH1 M4 (mount)
Computing Gear		
Printer	1	UCSC Computing
Laptops	7	UCSC Computing
Power cables & strips		UCSC Computing
Astro IIDC software licenses	7	Lab for AO, UCSC
USB keydrive	1	
Firewire cables	7	UCSC Computing
General Materials:		
Index cards	200	
Exacto-knife or razor blades	8	LAO
Transparencies (blank)	10	ISEE
Pushpins	1 box	
Clear plastic CD cover	4	
Assorted lenses	16+	LAO or UCB Vision Science Lab
Sticky poster pages	100	ISEE
Clear ziploc bags	30	
markers	20+	ISEE
Printed materials:		
Lab guidelines handout	70	
Aperture transparencies	8	w/variously shaped apertures of comparable sizes
Speaker evaluation rubric forms	70	
2D Fourier Transform handout	70	
Feedback forms	70	CfAO

b Lab Station Setup

As of August 2009, after borrowing supplies from the UCSC Lab for Adaptive Optics there were sufficient materials for seven Fourier Optics benches. As indicated in the Materials List, these benches consist of a CCD, plane wave source (laser), iris, and two lenses, each with its own mounts, posts, post holders, and post-holder brackets to mount on a one-meter rail. The laser plugs into wall outlets via a breadbox-sized power adapter, and the CCD connects to a computer via Firewire cable.



A cartoon schematic of the optical bench is shown above. Unless a standardized set of lenses is purchased, the exact position of the components on each bench will need to be determined individually. General alignment guidelines are:

- Align "downstream with the beam." Set up the laser about midway up in its post holder, and work down from there.
- Set up "flat toward focus" – keep the flat side of planoconvex lenses facing toward focal points, and the powered side facing collimated space
- Keep the beam centered on each optic – these regions have the highest surface quality.
- When aligning the CCD, remember that the actual detector is several centimeters behind the neutral density filter window. You may have to tilt the detector from side to side, or raise its post up and down, until you locate the beam on the detector.

The choice of lens arrangement will be dictated by the particular task a group is studying. For example, to best see the inner core of the PSF, use a faster lens to collimate the beam and a slower beam to focus the beam on the detector. The longer focal length expands the plate scale and allows finer details to be seen. This may be less important, though, for an investigation of speckles and the effects of phase errors when grosser phenomena may be of interest.

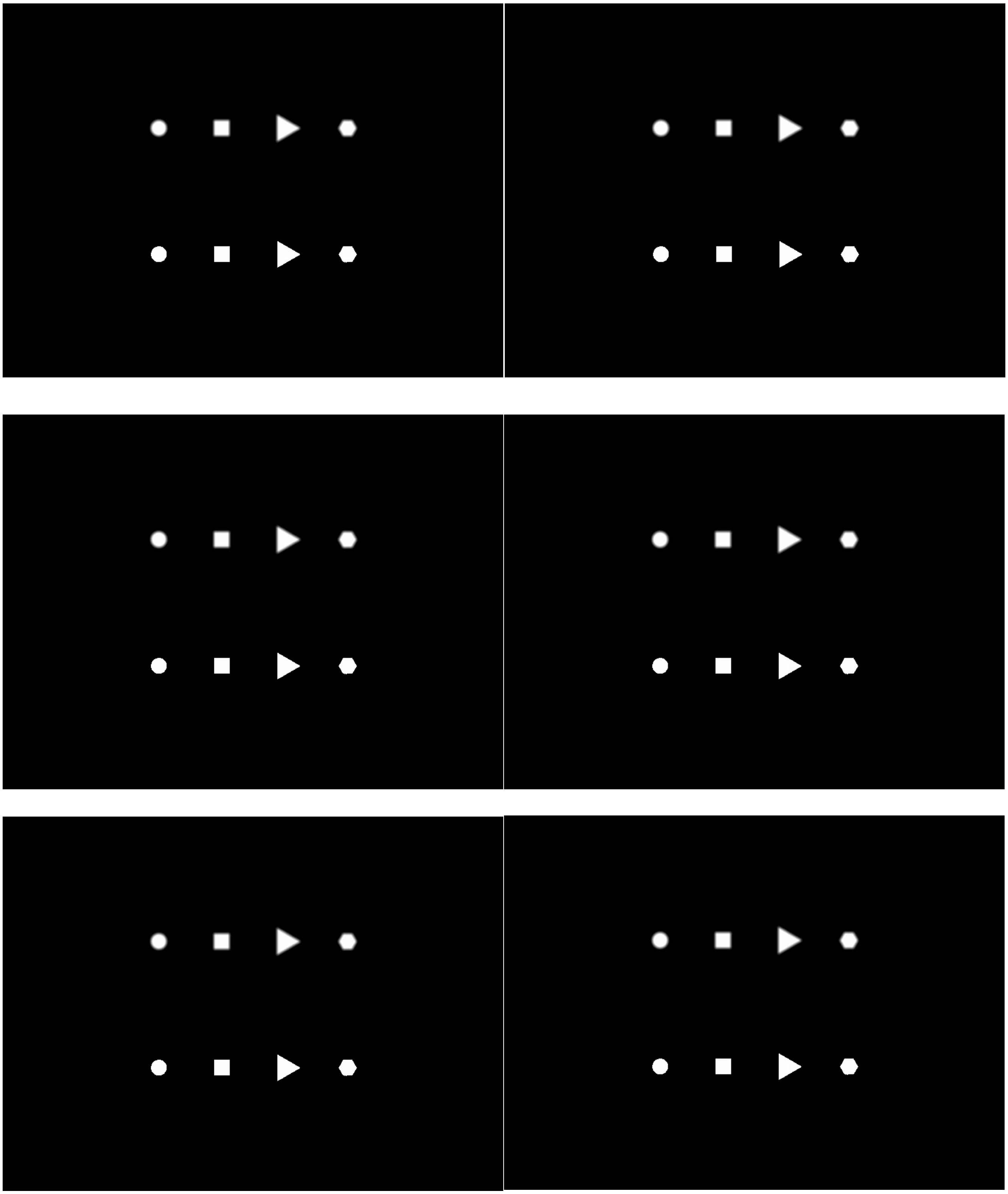
The current lenslet arrays used with this lab have too short a focal length (~2.7 cm) to bring collimated light to focus on the detector. Thus the spots must be reimaged, using a configuration similar to that for imaging the pupil. In this task the Thin Lens equation ($1/f = 1/o + 1/i$) will be your truest friend and ally, and it may also help to keep the (de)magnification of the beam in mind ($M = i / o$). The task is more easily accomplished by using the fastest available lens to reimage the spots and a slower lens to initially collimate the beam. For a pair of weak lenses it may actually be necessary to image the virtual spots rather than the spots themselves; you should probably just avoid this situation by making sure each station has both a weak and a strong lens.

Finally, the computers for this lab should be loaded with a minimum of:

- the CCD control software, AstroIIDC, which requires a software registration key (below)
- the IDL simulation software, FGUI
- either (a) registered IDL or (b) the IDL Virtual Machine

Optionally, the computers could also have image viewing software (e.g., SAO’s DS9) and/or image editing software to generate and print arbitrarily shaped apertures (e.g., ImageConverter, The Gimp, MS Paint, etc.).

c Aperture Maps:



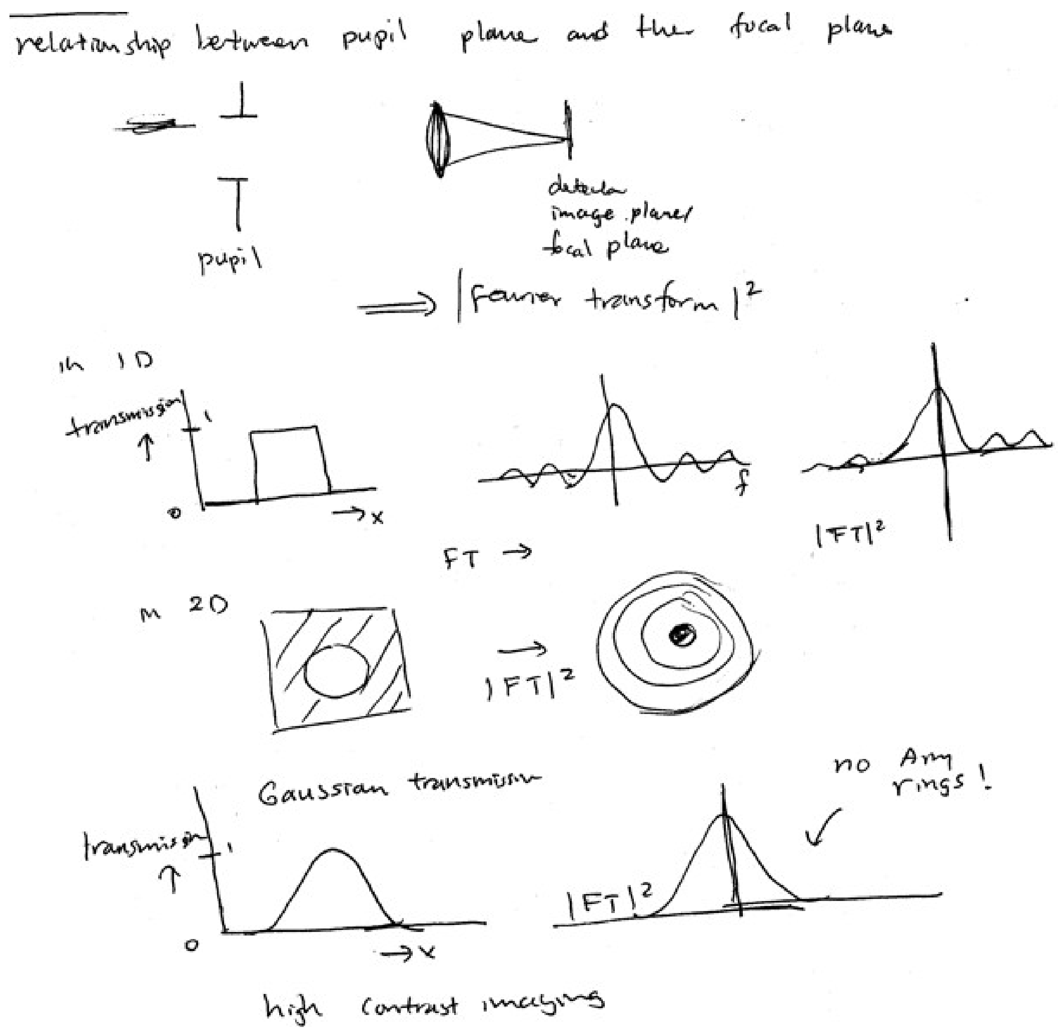
d Sample Investigation Questions:

1. "Good" questions we encourage relating to:
    1. Basic, general questions:
        1. What is a PSF?
        2. What are phase errors/aberrations?
    2. Aperture size & resolution
        1. What sets the scale of the size of the PSF?
        2. Why/how does the pinhole separation change the PSF?
        3. With two pinholes, would we get an interference pattern?
        4. Why does energy in the PSF spread out?
    3. Aperture shape & PSF structure
        1. How does aperture shape affect the PSF?
        2. How do apodized pupils work?
        3. Why do the cardboard cutout shapes make clearer PSFs than the printed shaped?
        4. What effect does the 'fuzziness' have?
        5. What determines how many PSF 'spikes?'
        6. Why does the slit have the opposite PSF orientation?
    4. Phase errors, speckles, and PSF structure:
        1. Why do phase errors make the PSF get wider even for small apertures?
        2. How do "wiggles" in phase go to high spatial frequencies?
        3. How do aperture edges relate to speckles? In what orientation?
        4. What does the PSF look like when the plastic bag is held still?
        5. Why does a lens before the pupil make the image so much larger?
        6. What is the effect of aberrations at different points in the light path?
        7. What is the effect of multiple layers of phase errors?
    5. Other good questions:
        1. What is the difference between near-field and far-field diffraction?
        2. What are some ways to achieve high-contrast imaging?
2. Questions to steer students away from:
    1. Why is the PSF aberrated by a plastic bag not symmetric?
    2. How would we correct for/account for the different shaped PSFs, e.g. From the hexagonal aperture?
    3. How are aperture and exposure time optimized?

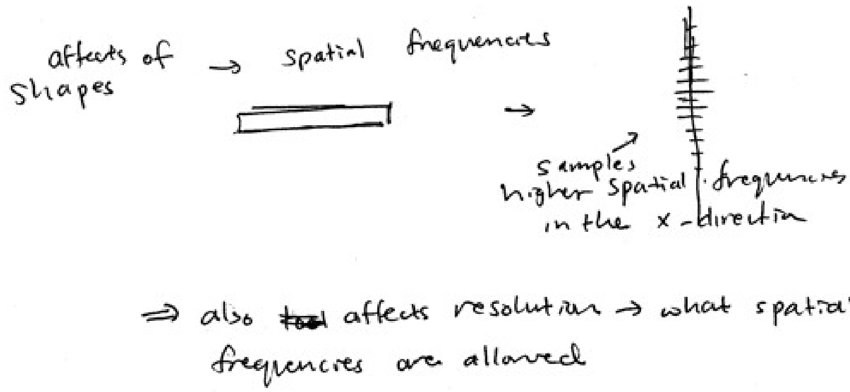
e Synthesis Talking Points

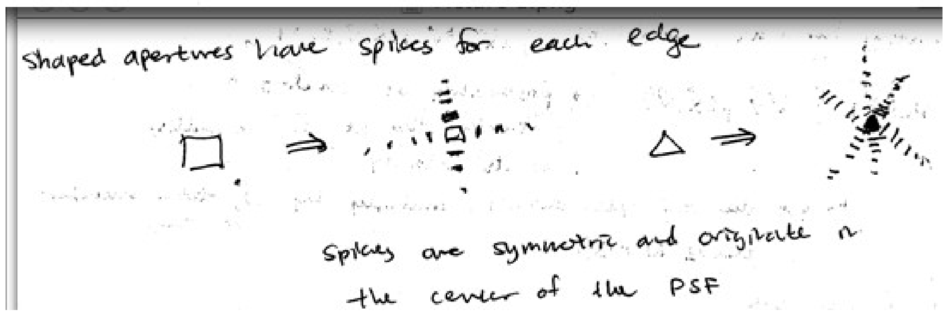
These are the points used by Tuan in his Synthesis talks at the 2009 AO Summer School. Use them as a guide, but be vigilant during the investigations and presentations for additional concepts, mistakes, or misconceptions to address.

1. Pupil plane and focal plane:

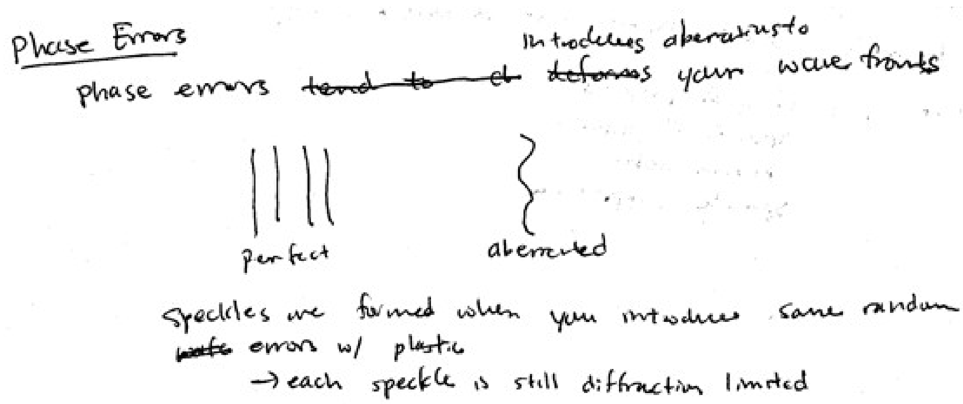


2. Aperture shape and PSF structure:

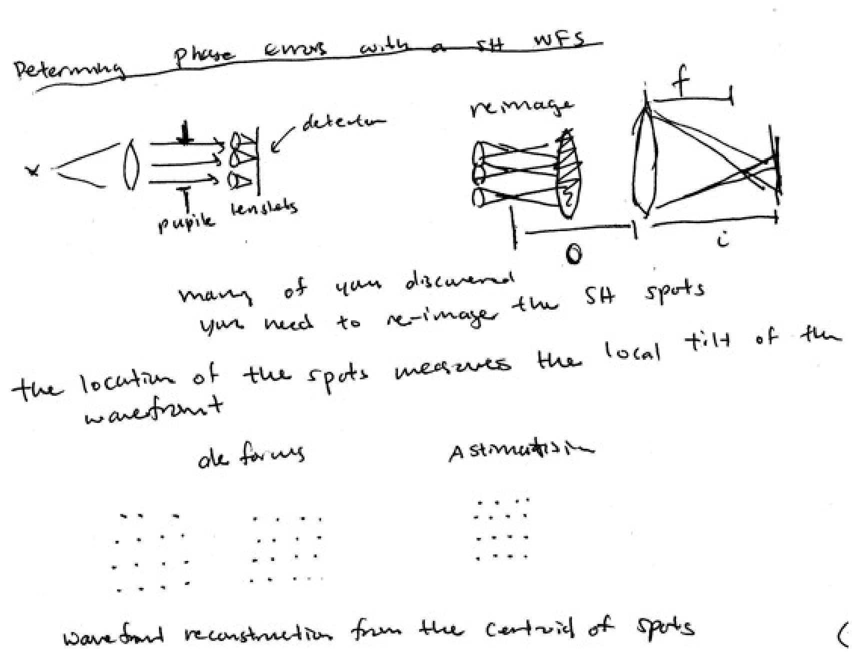




3. Phase errors:



4. Shack-Hartmann Sensors:



5. High-contrast imaging:
    1. The goal is to try to image faint things next to bright things
    2. Some strategies:
        1. Shaped pupils
        2. Apodized pupils
        3. Coronagraphs
        4. Speckle suppression

f   Lab Handout

The lab handout is on the following four pages:

Fourier Optics Lab

Center for Adaptive Optics Summer School

August 9–14, 2009

1 Introduction

The Fourier Optics activity is designed to enable you to observe and experiment with the diffraction of light. This activity uses a tabletop optical setup consisting of a computer-controlled detector illuminated by a laser source. You will work in small groups to investigate the relationships between the shape of the limiting aperture and the resulting far-field diffraction pattern. You will be able to directly examine how phase errors in the pupil affect the point spread function, as well as how they alter the signal received by a Shack-Hartmann sensor. The computer can be used to quantitatively examine the point spread function, and software tools are provided for comparing your experimental results with simulations.

This activity is conducted in two stages. In the first stage, you will investigate a series of optical phenomena that are present in the laboratory setup. In the later stage (§2), you will perform an investigation of a problem (or problems) of your choosing.

1.1 Optical Setup

The layout of the optical bench is shown in Figure 1. A 632 nm laser provides a reference point source, which is collimated by a lens. An iris is used as a limiting aperture — you may also place your own apertures in the collimated beam. A second lens then causes the beam to converge on a detector. The detector is a 480×640 array with 13 μm pixels. The lenses' focal lengths vary from station to station. Additional equipment includes a lenslet array, which can be used to simulate a Shack-Hartmann wavefront sensor. These lenslets have a 1 mm pitch and a 24 mm focal length.

A computer is connected to the detector and provides an interface to the CCD data. Note that "ghost" artifacts may be present in the image obtained by the detector. These are caused by internal reflections within the CCD chip and optical system, and should be ignored. Examples of such ghosts are shown in Figure 2.

You are free to modify the system as you see fit, including altering the positions of optical components. If you need a different piece of equipment for your investigation, feel free to ask your instructor.

Note: Please handle the lenses carefully. Also avoid touching the surface of the lenses as smudges from fingerprints or scratches on the lenses will affect the quality of the resulting images. Please use the lens paper when you need to put the lenses on some surface.

1.2 Materials

The materials for this activity include:

- cardboard, razor blades (for cutting apertures)

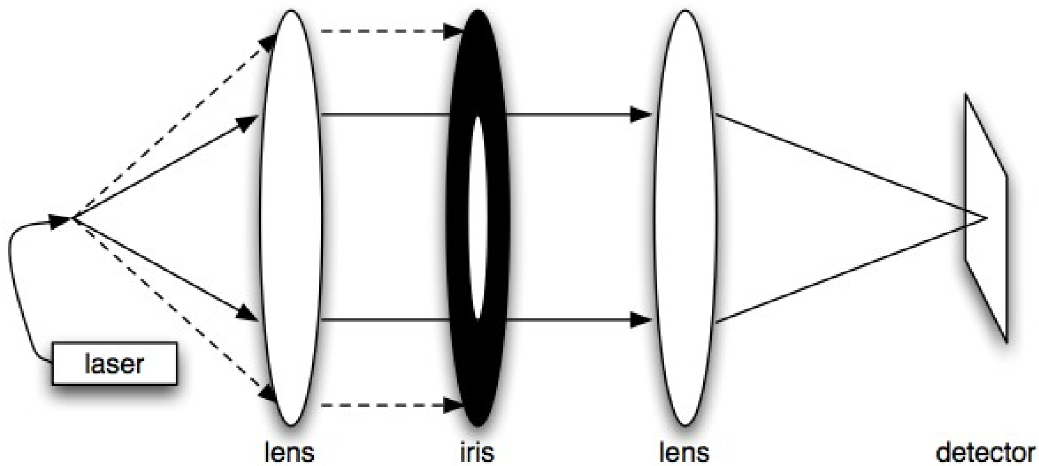


Figure 1: Layout of the Fourier Optics bench.

- pins (for making pinholes)
- plastic (for phase aberrations)
- trial lenses (for phase aberrations)
- transparency paper (for printing masks)

1.3 Software

Detector Interface The detector is controlled by a program called `Astro IIDC`. The interface in Figure 3 can be used to control the appearance of the pattern on the detector. Important controls are the *gamma*, *brightness*, and *exposure time*. The gamma is the index of a power-law stretch applied to the data values read from the CCD. A gamma of one represents a linear stretch. The brightness control amplifies the image (by applying a gain). The exposure time controls how long the detector integrates before being read out. All of these can be adjusted to bring out faint features in the diffraction pattern on the displayed image, though the brightness control can introduce noise at high settings. The 'Camera' menu item has functions for zooming in. Documentation of additional controls can be accessed via the software Help function.

Fourier Simulation An IDL computer program is provided to help in your investigations of diffractive phenomena. The primary purpose of this program is to simulate the far field diffraction pattern of several simple apertures with and without phase aberrations. Two different methods of introducing phase aberrations are available: a simulated phase screen with a Kolmogorov model of turbulence and aberrations decomposed into Zernike polynomials. For example, you can use the program to compare the effect of introducing an aberration like astigmatism to the optical system to the theoretical calculations. This program is available on the same computer that you are using to take images. Please feel free to ask for help using this program.

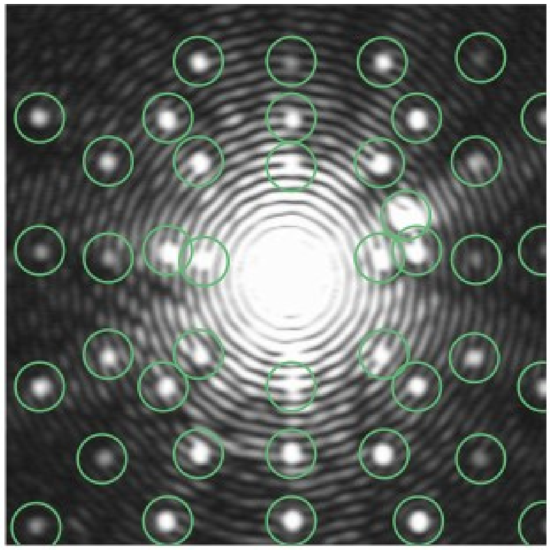


Figure 2: Location of ghost artifacts in an example CCD image.

The IDL language used for this graphical program can also be used for analyzing images and whatever data you see fit.

Drawing and Graphic Conversion The `Graphic Converter` software can be used to process images captured by the `Astro IIDC` software. It can also be used as a drawing program, where you can create aperture masks to be used in the optical setup. When printing a mask, be sure to select the appropriate paper feed for transparencies.

It is also possible to take screenshots of the detector display by using Apple+Shift+4, and then dragging a box over the region of interest. Images will appear as: Picture 1, 2, 3 ... on the desktop.

2 Avenues for Exploration (2nd Half)

1. A critical need for some astronomical observations is the ability to detect faint sources of light next to a bright one (e.g. a planet orbiting a distant star). Can you quantify what contrast levels are achievable by the system? What can you do to improve contrast limits?

2. Investigate how a Shack-Hartman wavefront sensor works: construct a WFS by adding the lenslet array to the optical setup. What are the spots and how do they give information about the wavefront? What would happen with a different number of lenslets? Predict what a simple aberration like defocus or astigmatism will do to the spots, and try to introduce such an error into the system. How would you use the information from the lenslets to remove the aberrations?

3. You are free to design an investigation of Fourier optical phenomena of your choosing. Define a problem and design a series of experiments to enhance your understanding. Feel free to consult an instructor for guidance.

Figure 3: Interface to the detector through the Astro IIDC software.

4

g Useful Vocabulary

It may be useful in future labs to provide the participants with a glossary with definitions of some of the important words in the field. To that end, here is a partial list of some of the terms often encountered in Fourier Optics:

Term	**Definition**
Aberration	
Aperture transparencies	
Apodize	
Contrast	
Diffraction	
Far-field	
Focal plane	
Fourier Optics	
Fourier Transform	
Ghost	
Image plane	
Interference	
Lenslet array	
Near-field	
Phase error	
Point Spread Function (PSF)	
Pupil plane	
Resolution	
Spatial Frequency	
Wavefront sensor	
Wavefront sensor	

h Feedback Form

LABORATORY ELEMENTS

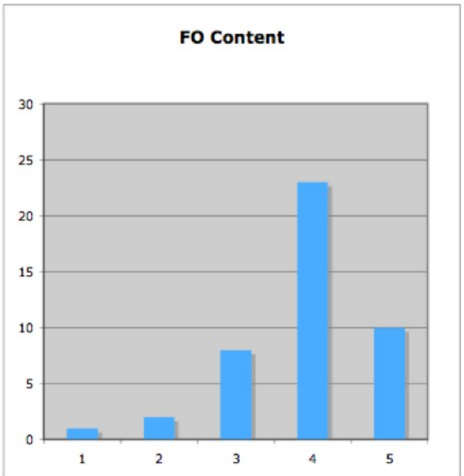
Please rate the following elements by circling your choice.
One (1) is the lowest/worst and five (5) is the highest/best.

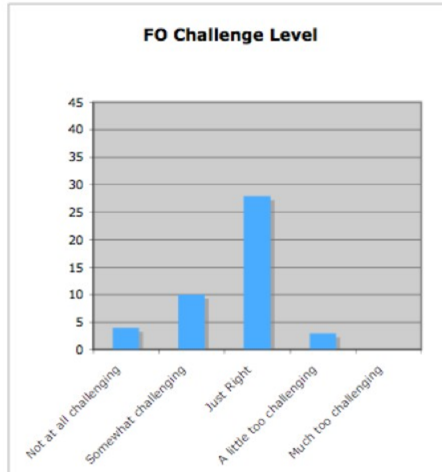
Fourier Optics

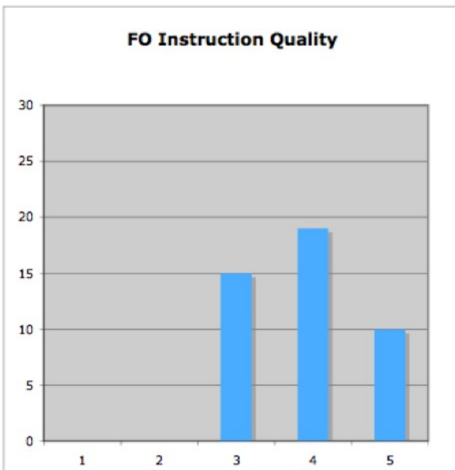
Content					
1	2	3	4	5	N/A
Quality of Instruction					
1	2	3	4	5	N/A
Level of Challenge					
Not at all challenging	Somewhat challenging	Just right	A little too challenging	Much too challenging	N/A
Format					
Much too open	A little too open	Just right	A little too directed	Much too directed	N/A
Overall Value					
Not at all Valuable	Somewhat Valuable	Valuable	Very Valuable	Extremely Valuable	N/A

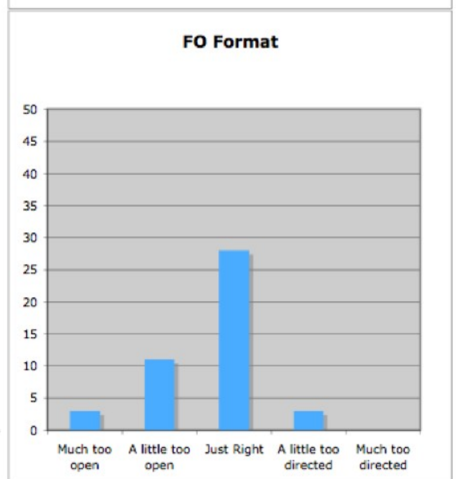
Additional Comments

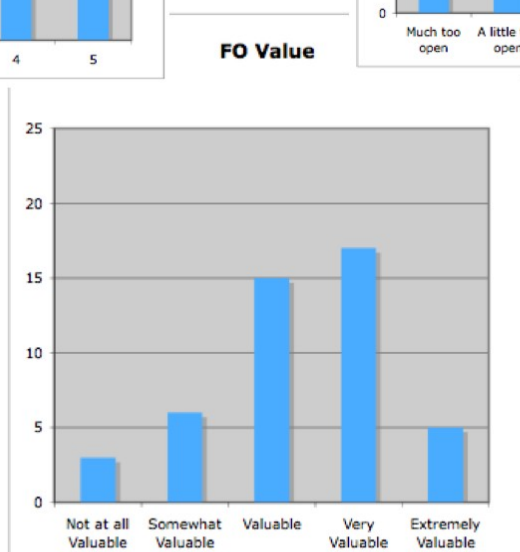
i Student Feedback











FOURIER OPTICS LAB

Please rate the "Content & Quality of Instruction" by circling your choice.
One (1) is the lowest/worst and five (5) is the highest/best.

Level of Challenge:

Not at all challenging; Somewhat challenging; Just right; A little too challenging; Much too challenging; N/A

Format:

Much too open; A little too open; Just right; A little too directed; Much too directed; N/A

Overall Value:

Not at all Valuable; Somewhat Valuable; Valuable; Extremely Valuable; N/A

#	Registration Category	Field of Study	Fourier Optics: Content	Quality of Instruction	Level of Challenge
1	Grad/Postdoc	Astronomy	4	5	Just Right
2	Grad/Postdoc	Astronomy	3	3	
3	Grad/Postdoc	Astronomy	4	3	A little too challenging
4	Grad/Postdoc	Astronomy	4	3	Just Right
5			4	3	A little too challenging
6	Grad/Postdoc	Astronomy	5	4	Just Right
7	Industry/Research	Free-Space Communications	4	3	Just Right

FOURIER OPTICS LAB

Please rate the "Content & Quality of Instruction" by circling your choice.
One (1) is the lowest/worst and five (5) is the highest/best.

Level of Challenge:

Not at all challenging; Somewhat challenging; Just right; A little too challenging; Much too challenging; N/A

Format:

Much too open; A little too open; Just right; A little too directed; Much too directed; N/A

Overall Value:

Not at all Valuable; Somewhat Valuable; Valuable; Extremely Valuable; N/A

#	Format	Overall Value	Additional Comments
1	Just Right	Valuable	My favorite part of the lab was the wavefront sensor segment. Learning to image the spots was particularly helpful. In general, giving presentations is useful, but in this case it ended up being a little silly, since all but one group made a WFS and most groups focused on talking about the 2nd half-it was pretty repetetive. It might have been better to specifically mention/tell us to present on 1st half investigations (or have them happen before we do the more single-challenge oriented section.)
2	A little too open	Valuable	• Some of the exploration seemed a little too open given the limits of the equipment. • Announcement of resources available. • Making groups spread out made doing a prefered task difficult.
3	Just Right	Very Valuable	Good!
4	A little too open	Very Valuable	This lab requires more than 3 hours. I think one day would be more valuable.
5	A little too directed	Valuable	
6	A little too directed	Very Valuable	The number of options for inquiry are limited in this lab. This leads to Frustration for students who can't explore their ideas. This could be fixed by using a lab manual with inquiry components. The "starters" divided the rows by subject and it was not clear that each station could do the same things. Keep students in same row, rotate out the facilitators.
7	Just Right	Valuable	During the course of the investigation, based on several group's observations, several questions were raised. Some of the questions were investigated in the later half by the different groups and they presented the reasoning behind the observations. But many questions were left unanswered and was not covered even in the synthesis section. It will be better if the synthesis section covers all these details.

8	Industry/Research	Astronomy	3	4	Somewhat challenging
9	Industry/Research	Astronomy	4	4	Just Right
10	Grad/Postdoc	Vision	5	5	Just Right
11	Grad/Postdoc	Vision	4	5	Just Right
12	Grad/Postdoc	Vision	5	5	Just Right
13	Grad/Postdoc	Astronomy	4	4	Somewhat challenging
14	Grad/Postdoc	Astronomy			Just Right
15	Grad/Postdoc	Astronomy	4	3	Just Right
16	Grad/Postdoc	Astronomy	5	5	Just Right
17	Grad/Postdoc	Astronomy	4	4	Just Right
18	Grad/Postdoc	Astronomy	5	5	Just Right
19	Grad/Postdoc	Astronomy	2	3	Not at all challenging
20	Grad/Postdoc	Military	4	4	Just Right

8	Just Right	Somewhat Valuable	It would have been nice to have more posts and mounts to add lenses in the optical train in a solid manner.
9	A little too open	Very Valuable	• More work w/the optics would be helpful. • More time to investigate the properties of the WFS we created would have been nice.
10	Just Right	Extremely Valuable	
11	Just Right	Very Valuable	Thanks for a great week!
12	Just Right	Valuable	
13	Just Right	Very Valuable	Note: I missed the first half of the lab.
14	Just Right	Extremely Valuable	I like this one. I wish we would have had a bit more guidance from our facilitator. The other group was struggling and we got a bit ignored. I'd never done an experiment using different shaped holes - ties nicely to telecopes (hexagon) very nice! Overall a lot of work went into this and it shows. Great effort from the facilitators & planner(s).
15	Just Right	Very Valuable	• This was a great lab for seeing (for the first time) the PSF in the laboratory. It was weird seeing "ghost" and other aberrations that I'm not used to seeing from only reading books and papers. • I enjoyed the first part of the lab better because I felt that I learned a lot more. • In the second half I chose the SH WFS. It was neat to actually build one in the lab but I felt that I didn't get adequate attention to my questions. • I had fundemental questions that were never answered :(
16	Much too open	Valuable	• Rushing through activities was not a good idea. At least for me, I have to be in an enviromnent without pressure to be able to think, and eventhough the pressure here was not in the possibility of "failing" - it seems this was encouraged through exploration - there was a real time constraint. Maybe next time focus on one/two experiments.
17	A little too open	Very Valuable	
18	Just Right	Extremely Valuable	More of this one! Please
19	Scientifically too open & Logistically much too directed	Not at all Valuable	
20	Just Right	Very Valuable	Facilitators were great!

21			3	4	Somewhat challenging
22	Student	Instrumentation	5	4	Just Right
23	Grad/Postdoc	Astronomy	3	3	Just Right
24	Industry/Research	Astronomy			
25	Industry/Research	Astronomy	3	3	Somewhat challenging
26	Grad/Postdoc	Astronomy	3	4	Somewhat challenging
27	Grad/Postdoc	Astronomy	4	4	Somewhat challenging
28	Grad/Postdoc	Astronomy	4	5	Just Right
29	Grad/Postdoc	Vision	5	4	Just Right
30	Grad/Postdoc	Vision	5	5	Just Right
31	Grad/Postdoc	Vision	3	3	Just Right
32	Grad/Postdoc	Astronomy	4	4	Just Right
33	Grad/Postdoc	High power lasers	4	4	Somewhat challenging
34	"Senior" postdoc, beyond 5-years	Vision	4	3	Just Right
35	Grad/Postdoc	Control Engineering	4	4	Just Right
36	Grad/Postdoc	Vision	2	4	Not at all challenging
37	Grad/Postdoc	Vision	3	3	Somewhat challenging
38					
39	Grad/Postdoc	Vision	4	3	Somewhat challenging
40	Industry/Research	Astronomy			Not at all challenging
41	Undergrad	Astronomy	4	4	Just Right
42	Grad/Postdoc	Astronomy	4	4	Just Right

21	A little too directed	Somewhat Valuable	It could be more advanced.
22	Just Right	Valuable	
23	Just Right	Valuable	
24			
25	A little too open	Valuable	
26	A little too open	Valuable	
27	A little too open	Valuable	
28	Just Right	Extremely Valuable	
29	Just Right	Very Valuable	
30	Just Right	Very Valuable	
31	A little too open	Valuable	
32	Just Right	Very Valuable	Building your own WFS is a very good experience!
33	Just Right	Valuable	
34	A little too open	Valuable	My own optics knowledge was quite rusty, hard to get up to speed, at least on this topic. Might benefit by a handout available to students (who are not physics/optics folks) before the summer school begins.
35	Just Right	Very Valuable	
36	A little too open	Somewhat Valuable	
37	Much too open	Somewhat Valuable	
38			
39	A little too open	Somewhat Valuable	The first part could have more ready made masks that would help understand Fourier transforms (e.g. slides with slits, sin patterns…)
40	Much too open	Not at all Valuable	Much too basic. Could have been done in a couple of minutes, except for the "filler" activities.
41	Just Right	Very Valuable	Instructors were helpful when they partially guided discussions. It would be good if instead of us having to ask, instructors could help with a complete explanation/correct after each activity instead of just at end of session. We still had unsolved questions at the end of the first activity (re pattern of ____ shape) which could have used clarification.
42	Just Right	Valuable	

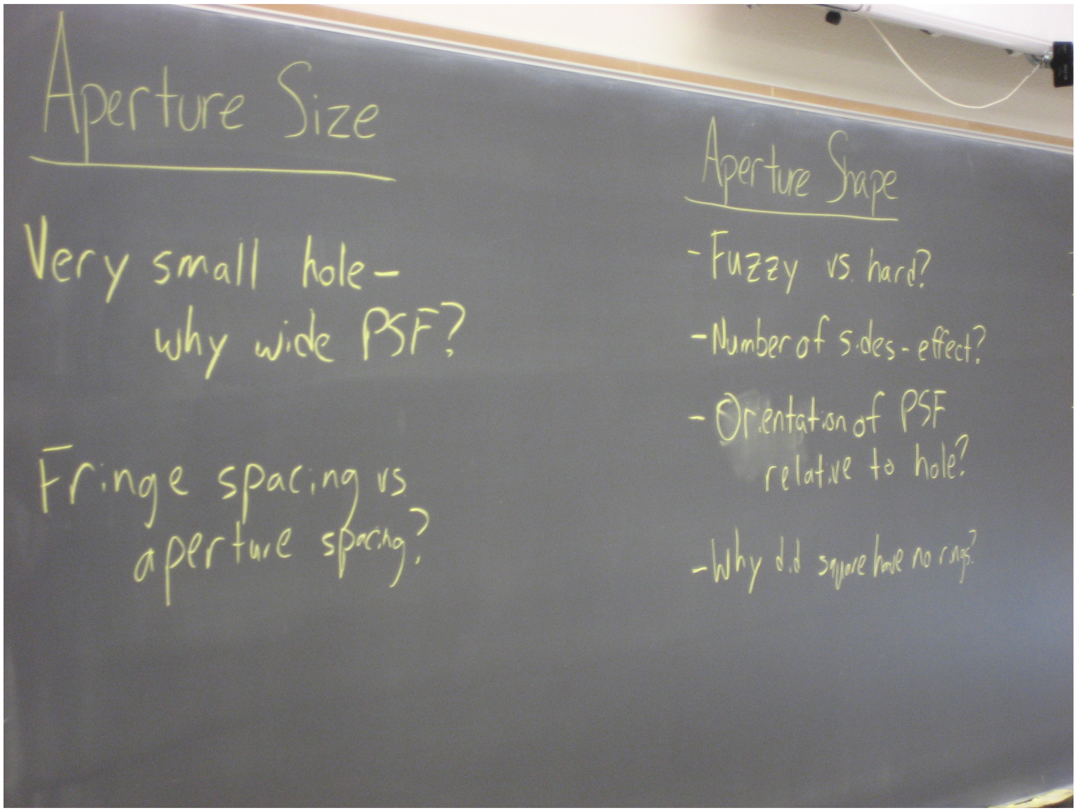
43	Grad/Postdoc	Astronomy	4	4	Just Right
44	Grad/Postdoc	Astronomy			
45	Grad/Postdoc	Astronomy	1	3	Not at all challenging
46	Grad/Postdoc	Astronomy	5	5	Just Right
47	Grad/Postdoc	Vision	4	3	Somewhat challenging
48	Industry/Research	Space & Military			
49	Industry/Research	Astronomy	5	5	Just Right
50	Industry/Research	Software for Astronomy	4	4	A little too challenging
			3.89	3.89	

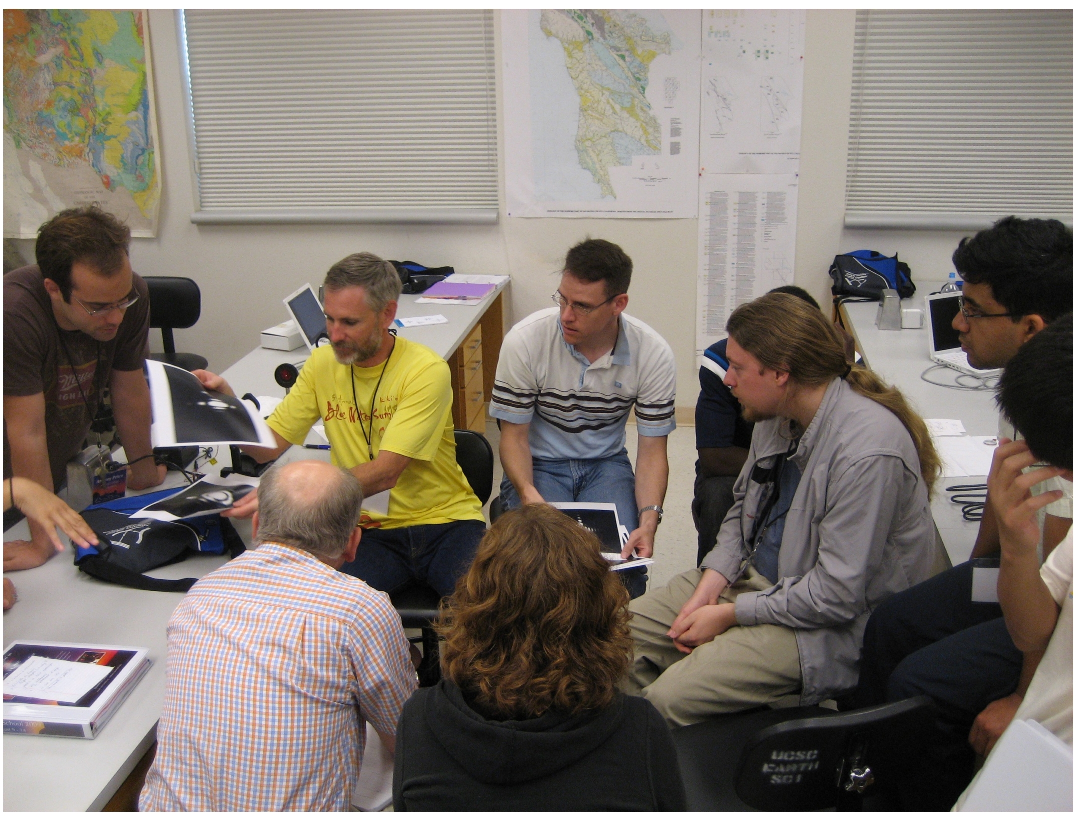
Not at all challenging	1	0	4
Somewhat challenging	2	0	10
Just Right	8	15	28
A little too challenging	23	19	3
Much too challenging	10	10	0
Much too open	44	44	45
A little too open			
Just Right			
A little too directed			
Much too directed			
Not at all Valuable			
Somewhat Valuable			
Valuable			
Very Valuable			
Extremely Valuable			

43	Just Right	Somewhat Valuable	
44			
45	Just Right	Not at all Valuable	Move this lab to the 1st day of the conference along with the other basic talks so that people have the option of skipping it.
46	Just Right	Extremely Valuable	
47	Just Right	Very Valuable	
48			
49	Just Right	Very Valuable	The inquiry style was preferable to other lab methods.
50	Just Right	Very Valuable	The Fourier Optics lab was a bit too dificult for me. Not having lab and optics experience it was too challenging. All in all it was a very nice and valuable experience. Thank you very much.

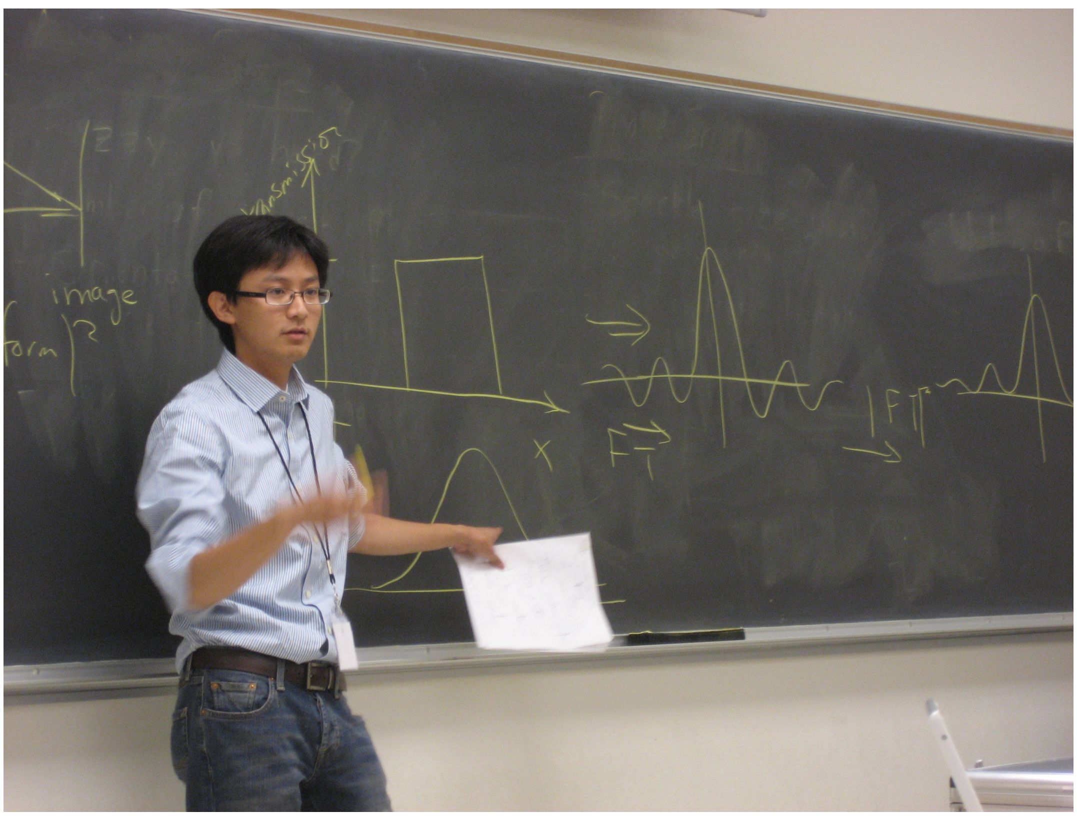
3	3
11	6
28	15
3	17
0	5
45	46

j Fourier Optics Photo Album

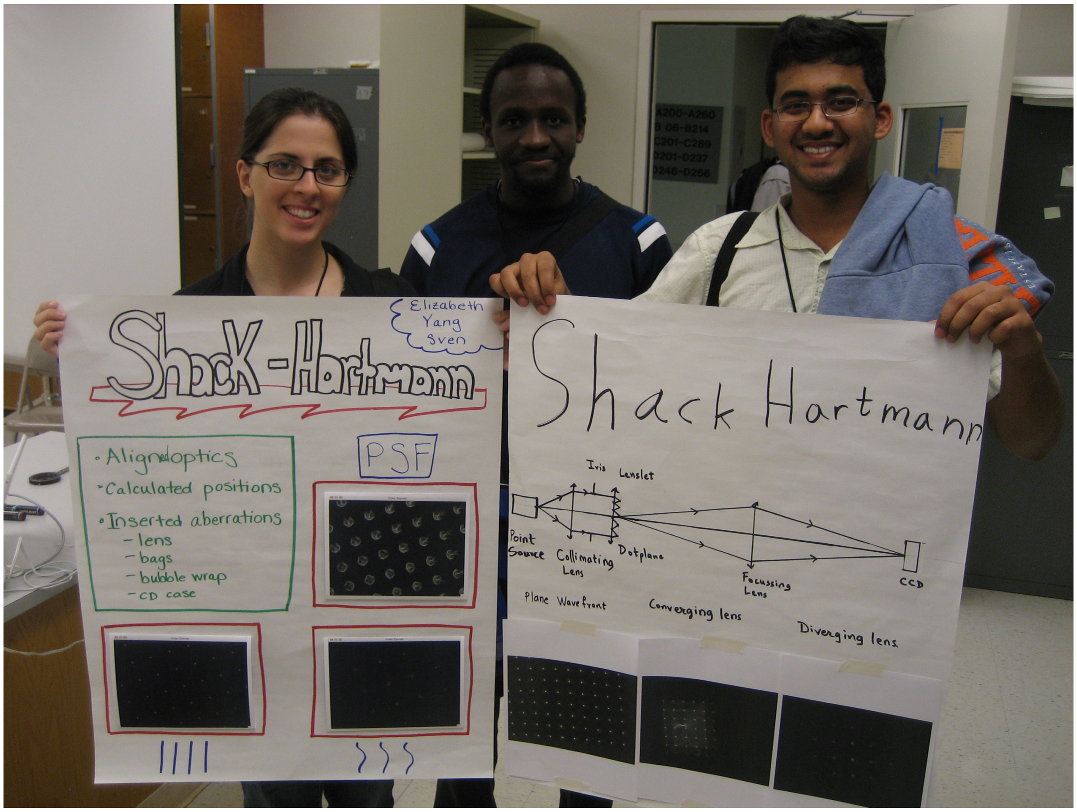

Aperture Size
Very small hole - why wide PSF?
Fringe spacing vs aperture spacing?
Aperture Shape
-Fuzzy vs. hard?
-Number of sides - effect?
-Orientation of PSF relative to hole?
-Why did square have no rings?




FOURIER OPTICS LAB
8:45-8:55 INTRO
8:55-9:10 STARTERS
9:10-9:18 ?GENERATION
9:20-10:10 INVESTIGATION 1
10:10-10:15 SHARE
10:15-10:45 BREAK
10:50-11:40 INVESTIGATION 2
11:45-12:05 PRESENTATIONS
12:05-12:15 SYNTHESIS
fuzzy square
hard square
Planet



image


Elizabeth
Yang
Sven
Shack-Hartmann
Alignedoptics
Calculated positions
Inserted aberrations
lens
bags
bubble wrap
CD case
PSF
Shack Hartmann
Iris
Lenslet
Point Source
Collimating Lens
Dotplane
Focussing Lens
CCD
Plane Wavefront
Converging lens
Diverging lens

k Goals, Met and Missed

Below is a list of the goals we originally set out for the Fourier Optics activity in Maui at the PDP, along with the evidence we said would convince us that the goals were actually met. As a final exercise for our activity, the design team members went back through these goals and tried to indicate, **based on the evidence available to us** (posters, talks, group discussions, questions posed, etc), how well we reached each of these goals. Since this is after the fact, we used a pretty coarse scale:

Scoring: **1**: 0-33% achieving **2**: 33-67% achieving **3**: 67-100% achieving

Content Goals Goal	Evidence	Comments	Score: 1-3
Participants construct and explain an optical diagram that demonstrates the function of each component in their setup	The correct drawing or explanation		2
Participants understand the connection between wavefront errors/aberrations and Shack-Hartmann spot locations/movements	A correct diagram/oral explanation	~1/3 of the participants investigated this topic, and they seemed to mostly understand this. 17 of 20 groups made SH systems. Although students understood that aberrations make the spots move, they did not make explicit the mechanism relating particular aberrations to particular motions.	1.5
Participants understand that wavefront errors/aberrations redistribute PSF core intensity into speckles outside the core	A correct diagram/oral explanation	~1/3 of the participants investigated this topic [WFE], but not all made this explicit I did not hear any students make this connection; this goal may require additional facilitation.	1
Participants understand the relationship between PSF (resolution and shape) and (aperture size and shape)	A correct diagram/oral explanation Participants explores high-contrast phenomena by varying aperture size/shape	Most people seemed to state/show this in one way or another 3 of 20 groups explored high-contrast phenomena; it's not clear why so few chose to do so.	3
Participants exhibit proper lab safety procedures and equipment treatment		Aside from the one bleeder (razor blade), no one was hurt/injured Several groups still followed the beam with their hands instead of cards, which could have soiled lenses or lenslets.	2.5

Participants understand the difference between the image/focal plane and the pupil plane	Participants correctly use the terms in conversation with each other, with facilitator, or during the presentation	I think at least half of my groups understood this.	2
Participants understand that phase errors introduced in different planes have different effects.	A qualitatively correct diagram/oral explanation	Perhaps two of the 8 "phase error" groups discussed this. Due to Ian's confusion, he actually facilitated *away* from this topic.	1
Process Goals Goal	Evidence	Comments	Score: 1-4
Participants will collaborate and work as effective members of a team	Participants talk to one another Participants explain coherently to each other, or to facilitators, what their group discovered/accomplished Are open to opinions of team members	My groups all worked very well together, from what I could see. No dominant team members. A few dominant team members, and a few people became disinterested in the first half of the lab and didn't come back after break.	3
Participants are able to accurately depict or record their observations			3
Participants appreciate the necessity of, and demonstrate and maintain, a properly calibrated apparatus.	E.g., image or spots are properly focused Participants mention/discuss calibration/alignment	Several of my groups tried to get all the SH spots on the detector, and attempted to get the best quality spots.	3
Participants define an investigable, directed question or problem		Some groups had difficulty picking a specific, particular aspect of Fourier Optics to investigate.	2.5
Participants stay on task			3
Attitudinal Goals Goal	Evidence	Comments	Score: 1-4
Participants develop a stronger connection to/with the Adaptive Optics community	Frank, open discussion between groups and group members	I'm not sure there was any evidence of this, or if we are really able to assess this. I had discussions with several of the participants outside the lab setting, both about the Lab and about AO in general; inasmuch as I connected with them, this goal was met.	1.5

CfAO Program Goals	Evidence	Comments	Score: 1-4
Students should draw on prior knowledge.		Several referred to lectures, one learner even opened up one of the .ppt presentations	3
Students should gain experience for jobs/careers.		Not sure if this is easy to assess here.	2
Students should be able to observe and communicate.		Most did a good job in explaining phenomena when asked and/or during presentation	2
Students should make predictions about phenomena		When asked to do so, they made reasonable predictions.	3

Other comments on the lab:

I think the additions/modifications made to this lab were successful overall. The starters allowed the students to investigate various phenomena and group themselves according to their common interests. I think this made their investigations more interesting and fun, as they likely felt ownership of their investigations, and they knew others in the group were interested in the same ideas. We might think of a more practical way to assess students during the lab, as the rubric forms were difficult to complete in such a short time period (during presentations).

I Possible improvements

Nothing mandatory here, but anyone re-designing this activity (or leading the version described herein) may want to keep a few possibilities in mind:

Facilitator suggestions:

- As an alternative to 'starter stations,' consider having all participants use a quick miniature lab plan that quickly takes them through the various Fourier Optics phenomena. You gain a few minutes by avoiding the structural downtime of starters; the challenge would be effectively facilitating such a rapid-fire activity.
- Instead of the end-of-lab presentations being made to the entire group, consider splitting the class into two and having two sets of presentations. This (1) lets students speak longer and/or (2) allows time for questions from the audience; the cost is that not all students hear about all investigated topics.
- Think of ways to better integrate the Fourier Optics Lab handout into the activity.
- Consider other possible handouts as well that might be useful to the students: e.g. (1) common Fourier Transform pairs or (2) a glossary of commonly used technical terms
- Extend the IDL "FGUI" software to simulate a Shack-Hartmann system. This is a big task!
- Have the CfAO or other trained educational professional (preferably one with optics experience) run a facilitation training workshop

Read through the student feedback for further suggestions on improving the lab.