OPT 561 — Advanced Imaging — Syllabus 2022

Description:

This course covers advanced topics in imaging, **concentrating on computed imaging, Fourier-transform-based imaging, and unconventional imaging, with emphasis on imaging through aberrating media** (particularly atmospheric turbulence), **in mathematical depth**. Topics include the following: stellar (speckle, Michelson, and intensity) interferometry, atmospheric turbulence, wavefront sensing for adaptive optics, phase diversity; pupil-plane lensless laser imaging including 2-D and 3-D digital holography, scattering and the Ewald sphere, synthetic-aperture radar, and phase-retrieval wavefront sensing for aligning telescopes and for optical metrology. Additional topics many also be selected from the following: exoplanet imaging by Lyot coronagraphy, imaging correlography, X-ray diffraction imaging, Fourier-transform imaging spectroscopy, structured-illumination superresolution, optical coherence tomography, and extended-depth-of-field imaging. The course also explores **image reconstruction and restoration algorithms** associated with these imaging modalities, including phase retrieval, maximum likelihood deconvolution, de-aliasing, side-lobe elimination, phase-error correction algorithms and computational issues. Additional topics suggested by the students are also considered.

A **project** plus term paper and presentation, exploring an advanced imaging topic in depth, including computer simulations (or laboratory experiments) and implementing the image formation or restoration algorithms, are required.

Prerequisites: OPT 461 (Fourier Optics) or OPT 463
This course fulfills the Physical Optics course requirement for MS Plan B students

Class Location:
Wilmot 116
This course is available entirely online.

Class Time: Mon. & Wed. 10:25am-11:40am
All lectures will be available to students online, either given during class time (and those will be recorded) or pre-recorded (in which case the class time will be used for Questions/Answers/Discussions).

Textbooks:

- J.W. Goodman's *Introduction to Fourier Optics 4th Ed.* will be reviewed and referenced heavily
- J.W. Goodman's *Statistical Optics*, 2nd Ed. (Wiley, 2015) [a few chapters, and homework problems from it]
- M.C. Roggemann & B. Welsh, *Imaging through Turbulence* (CRC Press, 1996) is useful but not required

Powerpoint lectures and pertinent journal papers will be made available

Grading

Grading for 2022:
15% homework
34% two mid-term exams worth 17% each
25% project term paper
20% presentation of project
5% class participation
1% sheets of notes for mid-terms
There will be no final exam: the project and presentation take its place

Notes on Spring 2022 schedule:
Classes start on Wednesday, Jan. 12 , 2022; the last class is Wednesday, April 27.
The last 3 or so classes will be used for the project presentation.
There will be no class on Monday, Jan. 17.
There will be no classes on Spring Break, which is the week of March 7.

Recitation Time
There is presently no recitation time for this course.

Topics covered in Spring 2022 (can be somewhat flexible)
First lecture: Background to Advanced Imaging.

Subsequent topics are as follows (with approximate number of lectures in parentheses; **topics in *italics* are optional and will be included only if there is a significant interest**; an existing topic can be swapped out to add a different topic suggested by students if there is sufficient interest):

Module 0: Introduction and background, and Review of Fourier Optics and conventional imaging (4)

1. Introduction and Review of Fourier Optics and conventional imaging (3-4) [FourierOpt, Ch.1-7]
    1. Introduction to advanced imaging
    2. Fourier transforms
    3. Wavefront propagation
    4. Imaging, PSFs, coherent & incoherent transfer functions

Module 1: Passive, incoherent imaging (13.5)

2. Imaging interferometry (2.5) [StatisticalOpt Ch.5]
    1. Amplitude/Michelson (vanCittert-Zernike) [SO 5.6]
    2. Intensity/Hanbury-Brown & Twiss [SO 6.3 (,9.5)]
    3. Rotating Slit Aperture (1) [presentation by J. Green, JPL]
3. Atmospheric Turbulence (2.5) [SO 8.4-8.7, Roggemann&Welsh 3.1-3.5]
    1. Turbulence theory
    2. Scintillation [Matt Banet]
4. Passive incoherent imaging through turbulence (4-5)
    1. Stellar speckle interferometry & phase retrieval (beyond OPT 461) [D&F paper, SO 8.8, R&W4.1-4.3, 6.3.4]

   2. ... and Knox-Thompson and Bispectrum [D&F, R&W4.4-4.5]
   3. Adaptive optics and wavefront sensors (Shack-Hartmann, shearing, ..) [R&W 5.1-5.3.2]
5. Image restoration (3)
   1. Review of Wiener-Helstrom Filtering
   2. Maximum Likelihood restoration (known PSF, unknown PSF: multi-frame blind deconvolution) [R&W 6.1-6.2.1];
   3. *Sparse interferometric imaging*
6. Coronagraphy (beyond OPT 461) (1)

Module 2: Active, coherent imaging (8.5 + *0.5*)

7. Phase-sensing (holographic/heterodyne/SAR/ultrasound) imaging (4)
   1. Coherent imaging: heterodyne sensing, review of speckle, ranging
   2. Phase-error correction (prom.pt., mapdrift, shearAve,) [papers]
   3. Turbulence correction by sharpening [papers]
   4. *Sidelobe mitigation (weighting functions, space-variant apodization) [papers]*
   5. 3-D imaging with frequency diversity (2-wave, multi-wave) [papers]
   6. 3-D imaging via Ewald sphere and rotation
8. Lensless coherent imaging by phase retrieval (2) (optical, imaging correlography, x-ray diffraction, ptychography) [papers]
9. Superresolution (2 – 3)
   1. *Optional: Beyond the pixel limit (De-aliasing) [papers]*
   2. Beyond diffraction limit: Gerchberg, Super-SVA [FO 6.6, papers]
   3. *Optional: Structured illumination [papers]*

Module 3: Wavefront sensing by phase retrieval and additional topics (2.5 +*2*)

10. Wavefront sensing by phase retrieval (2) [papers]
11. Phase diversity (1/2) [papers]
12. *Optional: Conventional imaging & WFS with partially coherent light (1) [SO7.2-7.3]*
13. *Optional: Advanced computational methods (1)*
    1. *FFT vs. DFT vs. CZT*
    2. *Sampling Q & Q'*
    3. *Nonlinear optimization*
    4. *Algorithmic differentiation*

- Other possibilities (time permitting): Extended depth of field imaging, Fourier telescopy, Fourier transform imaging spectroscopy, suggestions from students
  • Note there are 28 1.25-hour lecture periods including two mid-terms and 2 for presentations, leaving 23 periods versus 28.5 + *2.5* listed above, so not everything can be done.

The Project

- <u>Project + Report</u> (term paper): must be on some form of advanced imaging
  – Topic does not have to be something covered in lectures
  – Outline of topic and experiments <u>need approval by March 4</u>

  - More detailed reading + Doing:
  - Perform a realistic computer simulation + reconstruction experiment
    - Lab experiment can substitute computer simulations
  - Write "archival journal paper" summarizing the imaging technique, your experiment, and the results (15 to 25 typewritten pages, 12-pt font @ 1.5-space)
    - See Blackboard "Course Materials" for examples
    - Due on last day of classes: email .docx or .pdf file or upload to Blackboard
- Presentation:
- 20-minute (PowerPoint or similar) on project
  - As though giving a presentation at a conference
    - Email .pptx or .pdf file or upload to Blackboard
- During class time (unless most students are willing to schedule another time)
- In lieu of final exam

Instructional Activities

- **Lectures:** Most of the **lectures** will be given synchronously during the class period (Monday and Wednesday, 10:25 am – 11:40 am Eastern time, in Wilmot 116). They will be in-person for students who can come but remote for students who cannot be there physically. Attendance (in person or remote) is expected. Those lectures will be recorded for the benefit of those who are not available synchronously. Students should notify the lecturer if they are unable to attend.

  Note that the lecture slides are there to provide organization, equations, diagrams, and images; by themselves they are meant to be very incomplete; the words spoken in the lectures and extra sketches that might be presented during them are needed for completeness.

- **Videos and readings:** Some of the **lectures** might be pre-recorded. Watch the **videos** of the assigned lectures asynchronously on Blackboard (via Panopto) and read the **assigned readings** by their due dates

- **QuADs:** For pre-recorded lectures: After having watched the assigned pre-recorded lectures, attend and participate in the associated **Question/Answer/Discussion (QuAD) session**, which will be held during the regular class time periods (Monday and Wednesday, 10:25 am – 11:40 am Eastern time, in Wilmot 116). Attendance is expected. They will be in-person for students who can come but initially remote for the faculty, and for students who cannot be there physically. The faculty and the students who are remote will participate synchronously, via Zoom (use the link in Blackboard). These will be recorded for the benefit of remote students who cannot attend synchronously. Students may submit questions to the faculty ahead of time or ask synchronously. Participation in the QuADs (ask questions, contribute to discussions) will be reflected in the class participation portion of your grade. **Additional material that arises from discussions during the QuADs may be included in the exams**.

- **Message boards**: If requested by the students, slack channels for additional questions and discussions, allowing students to answer one another's questions, will be set up.

- **Faculty office hours:** The faculty will have drop-in office hours at the posted time (Thursdays at 4:00-5:00 pm Eastern time); in addition, appointments can be made for other times; send a request to the faculty by email.

- **TA office hours:** A TA will have office hours at the posted time (TBD); in addition, appointments can be made for other times. If an emailed question can be answered by email, the TA will try to answer it within 24 hours.

- **Study groups:** Students experience greater success by joining small study groups. You can learn from the readings, from your teacher, from the TA's, and from your peers. An effective way to learn something more deeply is to explain it to another student. Students will self-assemble in study groups, which can be in-person, via Zoom, or via a chat application such as Slack.

- **Additional help:** For help with studying more effectively and for tutoring, contact The Center for Excellence in Teaching and Learning (CETL), cetl@rochester.edu, (585) 275-9049, Dewey 1-15.

- **Homeworks:** Homeworks will typically be assigned every other Wednesday and will be due at 10:25 am Eastern time the Wednesday two weeks later. You do not really understand the material until you put it into practice by solving problems. Scan you homework solutions and upload them to Blackboard/Gradescope.

- **Exams:** There will be two mid-term exams. They will be held in synchronously during the regularly scheduled class time, a Monday or a Wednesday at 10:25-1:40 am, Eastern time (which can be in Wilmot 116 for those allowed to be on campus and wish to do so). Those taking an exam remotely will download the exam from Blackboard/Gradescope. All students will write their answers on paper, scan the answers to a PDF document, and upload those to Blackboard/Gradescope. The exams will be closed book. No electronic devices will be allowed except for the purpose of downloading the exam, uploading the answers, and communicating with the proctor of the exam. For each of two mid-term exams, the students shall put together a single page of notes on the covered material on an 8.5 x 11-inch sheet of paper. The notes can include any text, equations, diagrams, etc., hand-drawn or produced by a computer. During a mid-term exam, the student can use their sheet of notes for that exam, and for the second exam the sheet of notes for the first exam. The student will sign and upload the sheet of notes for that exam along with their answers to the mid-term exam. The sheet of notes for each mid-term exam will be given a grade of 0.5% of the total course grade if the sheet is at least half filled with material, or 0% if less than that. Each student should produce their own set of notes independently, since the preparation of the notes is a valuable learning tool.

Academic Honesty for OPT 561

— **Academic Honesty** policies will be enforced. Read the University of Rochester's policies on Academic Honesty. In addition, specific to OPT 561 are the following policies.

— **Exams**
For exams, you will be asked to write, on the first page of your answers, the following, as required by the Dean of Graduate Studies: "I affirm that I will not give or receive any unauthorized help on this exam, and that all work will be my own.", and write your name after that.

— **Homeworks**

- In OPT 561, working together is encouraged, and giving one another hints on homework problems is acceptable.
- Each student should write down his/her homework separately without looking at others'.
- Copying another's homework or copying <u>from any other source</u> or letting another copy your homework is <u>plagiarism</u> (falsely claiming someone else's work to be your own) and is forbidden.
- Homework is a small part of your grade. Think of the homework problems as practicing for the exams. If you cannot do the homework problems yourself, you will do poorly in the exams, which together count for much more.

— **Distribution of lecture videos, lecture slides, homeworks**
The lecture videos, the slides from the lecture videos, and the homework assignments and solutions are only for the students taking OPT 561 or by permission of the faculty. Posting them on a web site or allowing an unauthorized person to gain access to them is forbidden. These are all copyrighted materials. Unauthorized distribution will be considered a violation of academic honesty.

"Derive" and Mathematica™
For both homeworks and exams:

- When "proving" or "deriving" something for homeworks and exams
  - Show the detailed intermediate steps
  - Showing how you get to the answer is more important than getting the right answer
- Using Mathematica™ (or Maple™, etc.) for homework problems
  - You may <u>not</u> use it to get a result (solve equations) and then just report that result
  - Do show detailed intermediate steps
  - You <u>can</u> use Mathematica™ to check your results
  - You <u>can</u> use any software to make plots, images