Syllabus

Astronomy 289: Adaptive Optics and its Applications

Winter Quarter 2020, UC Santa Cruz

Instructor: Professor Claire E. Max

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Class Days: Tuesdays and Thursdays. First class January 7th, last class March 10th, 2020.

Class Times: 9:50-11:25 am Pacific Time, with a short break halfway

Location: Center for Adaptive Optics conference room (top floor)

Office Hours: Tuesday and Thursday, noon-1:00 pm Pacific Time
Other meeting times can be arranged by phone, e-mail, or in person

Web Site: The main class web site is http://www.ucolick.org/~max/289/ There is also a class website on UCSC's Canvas collaboration and learning environment. The Canvas title for our site is "ASTR-289-01" Reading material will be posted on the Canvas site. If you do not have access to the Canvas site (e.g. because you are not a UCSC student) please contact me.

Course Description:

Introduction to adaptive optics and its applications. The course is intended both for scientists who will be future users of adaptive optics systems, and for scientists and engineers interested in building and operating adaptive optics systems.

Topics include effects of atmospheric turbulence on astronomical images, basic principles of feedback control, wavefront sensors and correctors, laser guide stars, how to analyze and optimize performance of adaptive optics systems, and techniques for utilizing current and future systems for astronomical observations.

There will be two lectures a week (1.75 hrs each), a laboratory session using methods of inquiry based learning, and a class project in which student teams will design AO systems for applications that they are interested in.

Reading Materials:

a) Text book: "Field Guide to Astronomical Adaptive Optics", by Christoph U. Keller, Ramon Navarro, and Bernhardt R. Brandl, SPIE Books. An overview of optical design, detectors, telescopes, several types of instrumentation, opto-mechanics, vacuum and cryogenics, systems engineering, alignment and commissioning. A good read.

b) Reading materials for each lecture, distributed via the UCSC Canvas website. If you do not have access to the Canvas site please contact me.

Active Learning:

How people learn: Researchers studying how people learn have shown that the traditional passive lecture is far from the most effective teaching tool. It is not possible for an instructor to pour knowledge into the minds of students. It is the *students* who must actively engage in the subject matter and assimilate it in a manner that is meaningful to *them*. Hence this course will use several departures from the traditional lecture format, in order to encourage *active learning* and an understanding of the *concepts* rather than memorization of formulas and details.

Reading assignments will be more important in Astro 289 than in most science courses. Lectures will *presume* that you have done the required reading *beforehand*. To provide incentive for you to complete the reading assignments, I will ask you a few questions (either written or oral) about the reading at the start of each lecture.

Lectures will discuss the *underlying concepts and key points*, elaborate on the reading, and address potential difficulties. As feedback to the professor on whether students have a good grasp of the concepts discussed in class, lectures will include "Concept Questions." These will consist of short conceptual questions on the subject being discussed in the lecture. Students will be asked to first formulate their own answer, then to discuss their answer with each other, and finally to report each group's answers to the professor. The purpose of Concept Questions is to give feedback to the professor, to provide students with an environment for active learning, and to gain insight from discussions with your fellow students.

Laboratory exercises: We will use the Laboratory for Adaptive Optics for lab experiments. In these labs, students will have the opportunity for hands-on experience with the hardware and software components that make up an adaptive optics system. We will arrange alternative activities for those students not located in Santa Cruz.

Homework: Written assignments will be given every other week.

Project: Part way through the quarter, students will begin to work on class projects. These will be actively coached and facilitated. Students will choose a topic they are interested in, and will present their results to the rest of the class towards the end of the quarter.

Exams: There will be a take-home final exam. This exam will consist of both conceptual essay questions and quantitative problems.

Grading: Grades will be based on homeworks, the final exam, lab exercises, and projects.

Supplementary Reference Materials: (available in library of UCSC CfAO)

Optics by Eugene Hecht (Addison Wesley, 2002)

Adaptive Optics in Astronomy, edited by Francois Roddier (Cambridge University Press, 1999)

Principles of Adaptive Optics, fourth edition, by Robert K. Tyson, (CRC Press, 2015)

Selected Papers on Adaptive Optics and Speckle Imaging, edited by Devon G. Crowe, Milestone Series 93 (SPIE Press, 1994)

Selected Papers on Adaptive Optics for Atmospheric Compensation, edited by James E. Pearson, Milestone Series 92 (SPIE Press, 1994)

Statistical Optics, by Joseph Goodman (Wiley, 1985)

Introduction to Fourier Optics, by Joseph Goodman (McGraw Hill, 1996)

Electromagnetic Wave Propagation in Turbulence, by Richard J. Sasiela (Springer-Verlag, 1994)

Adaptive Optics for Vision Science, edited by Jason Porter, Hope Queener, Karen Thorne, and Abdul Awwal (Wiley, 2006)

Adaptive Optics for Biological Imaging, edited by Joel A. Kubby, (CRC Press, 2013)

Introduction to Image Stabilization, by Scott Teare and Sergio Restaino (SPIE Press, 2006)

Introduction to Wavefront Sensors, by Joseph Geary (SPIE Press, 1995)

Wavefront Sensing for Adaptive Optics in Astronomy, by Marcos van Dam (VDM Verlag, 2008)

Topics covered in Astro 289 (not necessarily in the order of their respective lectures)**:**

1. Overview. Why is adaptive optics needed? Where does atmospheric turbulence come from? Effects of turbulence on astronomical images. Basic components of adaptive optics systems. Some recent astronomical AO results. Applications of AO outside of astronomy.

2. Review of basic principles of optics. Optical aberrations. Ray-tracing and spot diagrams. Spherical aberration as the mother of all other third-order aberrations. Off-axis aberrations. Concepts of AO optical design.

3. Atmospheric turbulence and its effects on astronomical image formation. What determines index of refraction of air. Sources of turbulence: mirror seeing, dome seeing, boundary layer, free atmosphere. Role of Kelvin-Helmoltz instability. Turbulence profiles. Kolmogorov model of turbulence. Outer scale and inner scale. Reynolds number. Optical effects of turbulence: structure functions, long and short exposure images, anisoplanatism. Spectrum of index of refraction variations in the human eye.

4. Derivations of optical effects of turbulence: wavefront error, Fried parameter.

5. Other important turbulence parameters (isoplanatic angle, isokinetic angle, Greenwood frequency). Concept of wavefront error, and what it means. Image motion and tip-tilt. Strehl ratio. Basic architecture of adaptive optics and active optics systems: sensing, correction, and control in feedback systems. Concept of error budget, balancing error terms.

6. Wavefront sensing. Overview, main types of wavefront sensors, Shack-Hartmann sensors and centroiding for a quad cell geometry. Signal to noise ratio of a detector. Pyramid sensors and curvature sensing. Advantages and disadvantages of different types of wavefront sensor. Detectors used for wavefront sensing.

7. Wavefront correctors: General principles of dividing pupil into subapertures. Fitting error. Actuators. Deformable mirror design requirements. Main types of deformable mirrors, factors affecting their practical performance. Segmented vs. continuous face-sheet mirrors. Influence functions. Adaptive secondary mirrors. Bimorph mirrors. MEMS mirrors. Membrane mirrors. Fitting error revisited.

8. Image motion and tip-tilt. Effect of tip-tilt errors on Point Spread Function and Strehl ratio.

9. How to analyze and optimize adaptive optics system performance: basic principles of systems analysis and error budgets. Effect of AO design parameters on PSF, encircled energy, energy through a spectrograph slit. Balancing bandwidth error against measurement error. Balancing subaperture size against measurement error.

10. Laser guide stars for astronomy. Anisoplanatism and the need for laser guide stars in order to increase sky coverage. When and why are laser guide stars needed? Principles of laser light scattering (Na and Rayleigh). LIDAR equation. Sodium layer. Sodium atom modeled as a two-level system. Line broadening mechanisms.

11. Laser guide stars, continued: Saturation effects in the sodium layer. Effect of pulse format on how much light is returned. Principles of laser action. Lasers used for Rayleigh guide stars. Lasers used for sodium guide stars. Performance analysis various laser guide star AO systems.

12. Tip-tilt correction. Tilt anisoplanatism: physical origin, equations, scaling with wavelength and telescope size. Tip-tilt system configuration. Tip-tilt sky coverage. Factors contributing to additional wavefront error for laser guide stars: spot elongation, finite spot size, cone effect. Error budgets and expected Strehl performance.

13. Detectors, signal to noise ratio. Techniques for astronomical observations with current adaptive optics systems. How do you know what to believe about your data? Choice of system parameters such as AO gain and bandwidth, issues in measuring the adaptive optics point spread function, limitations of adaptive optics for imaging and for spectroscopy.

14. Point spread function (PSF), deconvolution, PSF subtraction. Methods for measuring point spread function. Methods of PSF subtraction. Deconvolution.

15. Control systems and wavefront reconstruction. Principles of feedback control. Introduction to the basics of control systems, practical implementation of control systems for adaptive optics applications. Gain, bandwidth error.

16. The future of astronomical adaptive optics: Systems with very precise wavefront correction – Extreme AO for extrasolar planet detection. Next-generation AO systems for 8m – 40m ground-based telescopes: tomography, Multiconjugate AO, Multi-Object AO, Ground-Layer AO.

17. Adaptive optics applications in Vision Science.

Academic Honesty and Plagiarism: Academic dishonesty and plagiarism undermine the efforts of honest students, the value of a UC Santa Cruz degree, and the integrity of the university as an institution. Cheating or plagiarism in any part of the course may lead to failing the course and suspension or dismissal from the University. What is plagiarism? In short, it is presenting someone else's work as your own. Examples include using text from a published source or from the web without attribution, copying another student's written homework assignment, or allowing your own work to be copied. You are encouraged to discuss homework problems with fellow students, but your collaboration must be at the level of ideas and concepts only. Your homework, project reports, etc. must be written <u>in your own words</u>. Legitimate collaboration ends when you "lend", "borrow", or "trade" written solutions to problems, or in any way share in the act of writing your answers.

The official UCSC policy concerning academic integrity can be found at

http://www.ucsc.edu/academics/academic_integrity/index.html

The American Astronomical Society Code of Ethics makes for thoughtful and interesting reading. It can be found at https://aas.org/policies/ethics