Welcome to ...

2.717J/MAS.857J
Optical Engineering
This class is about

- **Statistical Optics**
  - models of random optical fields, their propagation and statistical properties (*i.e.* coherence)
  - imaging methods based on statistical properties of light: coherence imaging, coherence tomography
- **Inverse Problems**
  - to what degree can a light source be determined by measurements of the light fields that the source generates?
  - how much information is “transmitted” through an imaging system? (related issues: what does _resolution_ really mean? what is the space-bandwidth product?)
The van Cittert-Zernike theorem

Galaxy, ~100 million light-years away

Very Large Array (VLA)

Radio waves

Cross-Correlation + Fourier transform

Image credits:
- hubble.nasa.gov
- www.nrao.edu

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Optical coherence tomography

Image credits: www.lightlabimaging.com

Coronary artery

Intestinal polyps

Eosophagus

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Inverse Radon transform
(aka Filtered Backprojection)

The hardware

The principle

Magnetic Resonance Imaging (MRI)

Image credits:
www.cis.rit.edu/htbooks/mri/
www.ge.com

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You can take this class if

• You took one of the following classes at MIT
  – 2.996/2.997 during the academic years 97-98 and 99-00
  – 2.717 during fall ’00
  – 2.710 during fall ’01
  OR
• You have taken a class elsewhere that covered Geometrical Optics, Diffraction, and Fourier Optics

• Some background in probability & statistics is helpful but not necessary
Syllabus (summary)

- Review of Fourier Optics, probability & statistics 4 weeks
- Light statistics and theory of coherence 2 weeks
- The van Cittert-Zernicke theorem and applications of statistical optics to imaging 3 weeks
- Basic concepts of inverse problems (ill-posedness, regularization) and examples (Radon transform and its inversion) 2 weeks
- Information-theoretic characterization of imaging channels 2 weeks

Textbooks:
What you have to do

• 4 homeworks (1/week for the first 4 weeks)
• 3 Projects:
  – Project 1: a simple calculation of intensity statistics from a model in Goodman (~2 weeks, 1-page report)
  – Project 2: study one out of several topics in the application of coherence theory and the van Cittert-Zernicke theorem from Goodman (~4 weeks, lecture-style presentation)
  – Project 3: a more elaborate calculation of information capacity of imaging channels based on prior work by Barbastathis & Neifeld (~4 weeks, conference-style presentation)
• Alternative projects ok
• No quizzes or final exam
Administrative

• Broadcast list will be setup soon
• Instructor’s coordinates
  George Barbastathis
• *Please do not phone-call*
• Office hours TBA
• Class meets
  – Mondays 1-3pm (main coverage of the material)
  – Wednesdays 2-3pm (examples and discussion)
  – presentations only: Wednesdays 7pm-??, pizza served
The 4F system

\[ g_1(x, y) \]

object plane

\[ G_1 \left( \frac{x''}{\lambda f_1}, \frac{y''}{\lambda f_1} \right) \]

Fourier plane

\[ g_1 \left( -\frac{f_2}{f_1} x', -\frac{f_1}{f_2} y' \right) \]

Image plane
The 4F system

\[ G_1(u, v) \]

\[ u = \frac{\sin \theta_x}{\lambda} \]

\[ v = \frac{\sin \theta_y}{\lambda} \]

\[ g_1(x, y) \]

object plane

\[ G_1 \left( \frac{x''}{\lambda f_1}, \frac{y''}{\lambda f_1} \right) \]

Fourier plane

\[ g_1 \left( -\frac{f_1}{f_2} x', -\frac{f_1}{f_2} y' \right) \]

Image plane
The 4F system with FP aperture

\[ G_1(u, v) \times \text{circ} \left( \frac{r''}{R} \right) \]

Object plane:
\[ g_1(x, y) \]

Fourier plane: aperture-limited
\[ (g_1 * h) \left( -\frac{f_1}{f_2} x', -\frac{f_1}{f_2} y' \right) \]

Image plane: blurred (i.e. low-pass filtered)

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The 4F system with FP aperture

Transfer function: circular aperture
\[ \text{circ}\left(\frac{r''}{R}\right) \]

Impulse response: Airy function
\[ \text{jinc}\left(\frac{r'R}{\lambda f_2}\right) \]
Coherent vs incoherent imaging
Coherent vs incoherent imaging

Coherent impulse response
(field in $\Rightarrow$ field out)

$h(x, y)$

Coherent transfer function
(FT of field in $\Rightarrow$ FT of field out)

$H(u, v) = \text{FT}\{h(x, y)\}$

Incoherent impulse response
(intensity in $\Rightarrow$ intensity out)

$\tilde{h}(x, y) = |h(x, y)|^2$

Incoherent transfer function
(FT of intensity in $\Rightarrow$ FT of intensity out)

$\tilde{H}(u, v) = \text{FT}\{\tilde{h}(x, y)\} = H(u, v) \otimes H(u, v)$

$|\tilde{H}(u, v)|$: Modulation Transfer Function (MTF)

$\tilde{H}(u, v)$: Optical Transfer Function (OTF)
Coherent vs incoherent imaging

Coherent illumination

Incoherent illumination
Aberrations: geometrical

- Origin of aberrations: nonlinearity of Snell’s law \( n \sin \theta = \text{const.} \), whereas linear relationship would have been \( n \theta = \text{const.} \).
- Aberrations cause practical systems to perform \textit{worse} than diffraction-limited.
- Aberrations are best dealt with using optical design software (Code V, Oslo, Zemax); optimized systems usually resolve \( \sim 3-5\lambda \) (~1.5-2.5\,\mu m in the visible)
Aberrations: wave

Aberration-free impulse response \( h_{\text{diffraction}}(x, y) \)

Aberrations introduce additional phase delay to the impulse response

\[
\tilde{h}_{\text{aberrated}}(x, y) = h_{\text{diffraction}}(x, y) e^{i\phi_{\text{aberration}}(x, y)}
\]

Effect of aberrations on the MTF

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