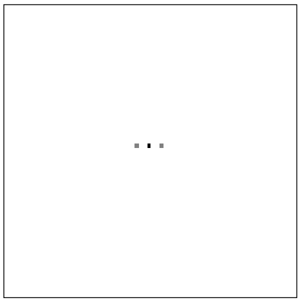
Lecture 17 – Spatial filtering, the MTF

REVIEW

Q. What information is contained in the **spatial frequency spectrum** (Fourier transform) of an image?

A. The frequencies, orientations and contrast of sine wave gratings contained in the image.



0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	**0.5**	0.0	0.0	**1.0**	0.0	0.0	**0.5**	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Figure 1. Gray-scale plot of the data contained in the spatial frequency spectrum of an image, with a sample of the numbers from the center of the data array.

Q. What do the low spatial frequencies contribute to an image?

A. The large luminance variations and large features in the image.

Q. What do the high spatial frequencies contribute to an image?

A. Edges and fine details.

Q. What is spatial filtering?

A. A process by which certain spatial frequencies are removed from the image.

Q. What would an image look like if the high spatial frequencies were filtered out?

A. Blurred

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	**0.4**	0.0	0.0	0.0
0.0	0.0	0.0	0.0	**0.5**	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	**0.5**	0.0	**1.0**	0.0	**0.5**	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	**0.5**	0.0	0.0	0.0	0.0
0.0	0.0	0.0	**0.4**	0.0	0.0	0.0	0.0	0.0

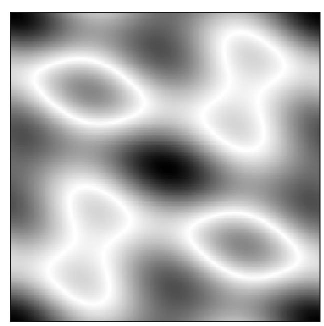


Figure 2. The array of numbers is the center portion of a Fourier spectrum. If we take the inverse Fourier transform of the spectrum, it produces the image on the right.

For any image you can compute its Fourier transform, which gives you the spatial frequency spectrum of the image. The two data sets, the spatial image and its spatial frequency spectrum, are a pair that are linked together by the mathematical process of Fourier transformation. Figures 3 shows the examples we used in Lab 5 of a spatial image and its spatial frequency spectrum.

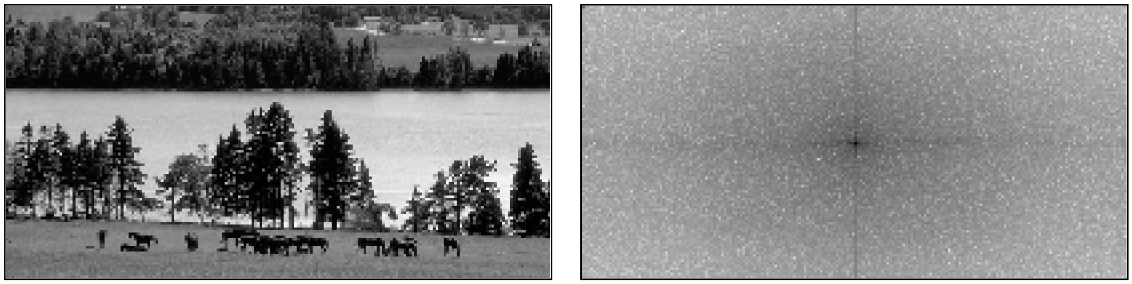


Figure 3. Example of a spatial image (L) and a gray-scale plot of its spatial frequency spectrum (R)

Q. Why does the frequency spectrum have darker (higher) values along the horizontal and vertical midlines?
A. It indicates that certain features in the image must be made using fairly high contrast vertical and horizontal sine wave gratings.

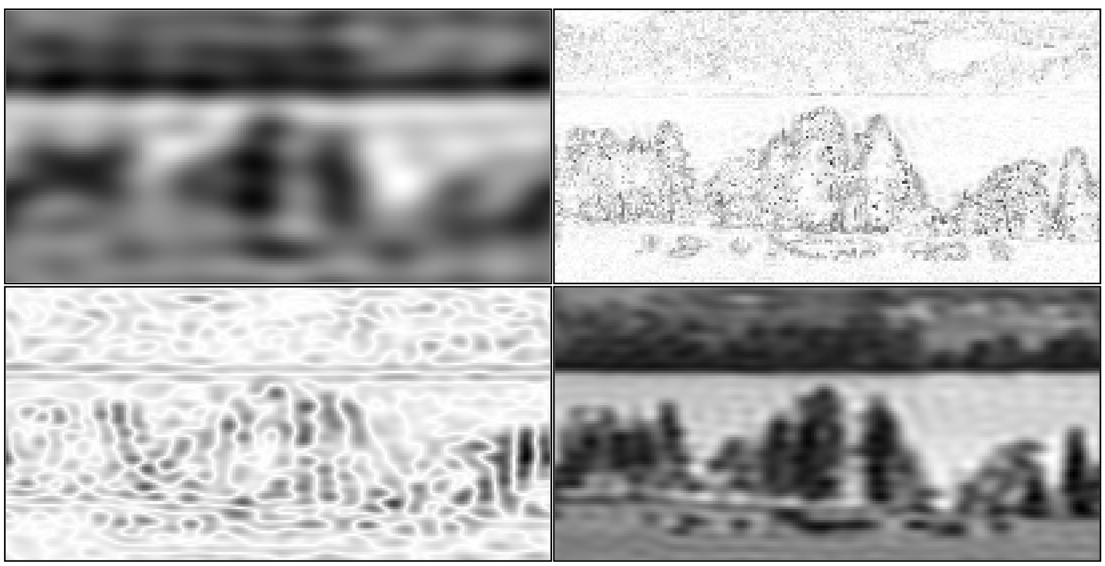


Figure 4. Four version of the image in Fig. 3 that have been spatially filtered

Figure 4 shows four images that are spatially filtered versions of the image shown in Figure 3.
Q. Can you identify the type of filtering that was performed on each image?
A. Upper left: Low-pass filtered image made of only very low spatial frequencies.
Upper right: High-pass filtered image made of only high spatial frequencies.
Lower left: Band-pass filtered image with both low and high frequencies filtered out.
Lower right: Low-pass filtered that include higher frequencies that the upper-right image.

Other examples of Fourier spectrum/spatial image pairs from the Image Processing Handbook (2nd Edition, Russ, CRC Press 1995).
Refer to Figures 10, 16, 17, 53

Another example of Fourier transformation and spatial filtering is illustrated in Figure 5, below. The left image shows a raw Shack-Hartmann aberrometer image. A Shack-Hartmann aberrometer projects a tiny beam of light into the eye and then measures the light reflected out. The beam reflected out of the eye passes through an array of microscopic plus lenses that break the broad beam up into many smaller beams. Light from each beam is focused to a spot, so the raw data image looks like a circular array of spots on a black background. In order to compute the optical aberrations of the eye, we must analyze the location of each of the spots. The analysis, therefore, requires that we locate the positions of each spot, but some, especially those near the edge are fainter and hard to see.

Q. Based on what you have already learned, why do the dots near the edge of the pupil appear dimmer?
A. The Stiles-Crawford Effect

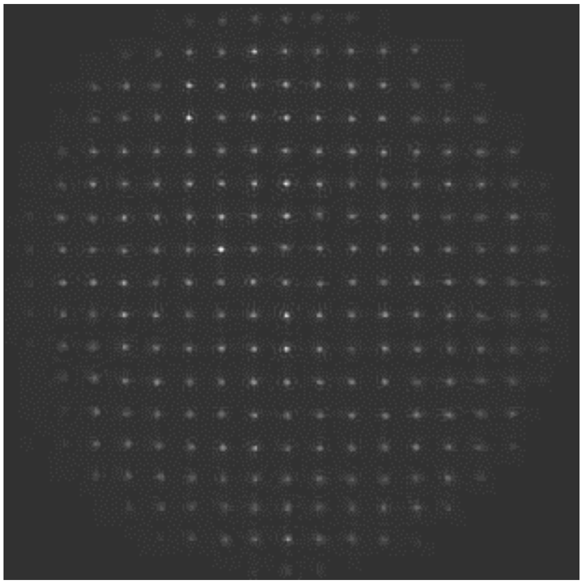
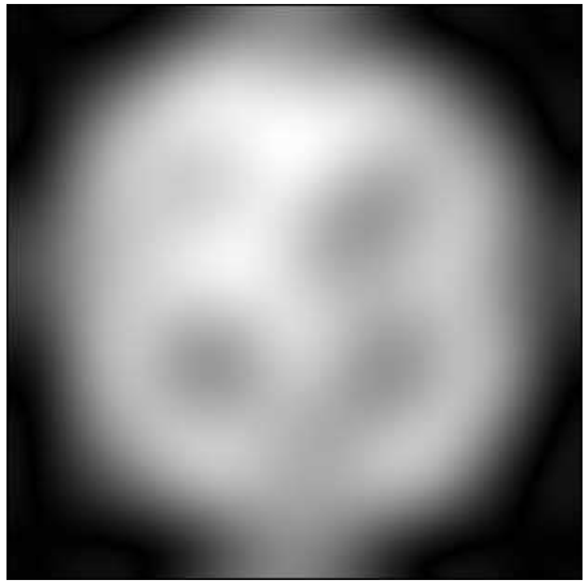
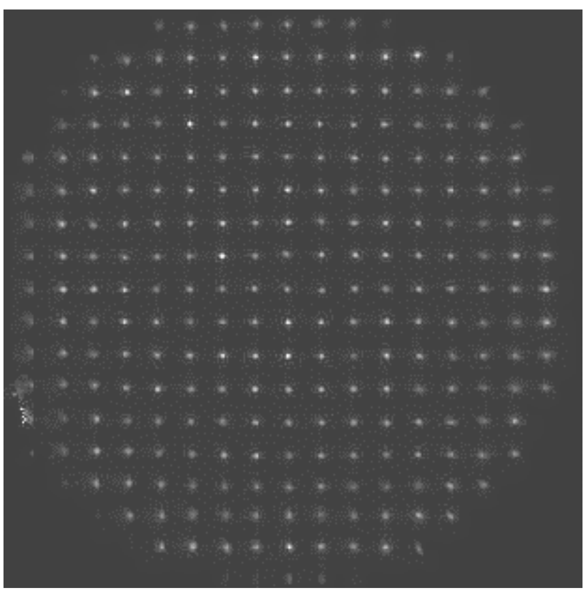




Figure 5. Raw data (upper left) was divided by the low-pass-filtered version of the same image (upper right) to even out the brightness of the dots. The result (left) shows more uniform dot brightness.

In order to improve Shack-Hartmann analysis across the whole pupil, I needed to brighten the peripheral dots. To do so, I did the following:

- Fourier analyzed the raw data image (upper left)
- Low-pass filtered the spectrum (threw away everything except the lowest spatial frequencies)
- Computed the inverse Fourier transform of the low-pass filtered spectrum (upper right image) This gave the overall, gradually variation in image brightness that caused some dots in the original image to be dimmer than others. This was a low-passed filtered version of the original image.

- Divided the luminance values in the original image (upper left) by the low-pass filtered image (upper right) to produce the corrected image below. Notice that the brightness of the dots is more uniform. That simplified analysis of the location of dots in the peripheral pupil.

Clinical aberrometry - another application of Fourier optics

- Aberrometers are instruments used in pre-op cataract evaluation to estimate the visual acuity expected after cataract surgery.

  Q. Why is it important to estimate post-op visual acuity?
  A. The cataract interferes with vision and prevents a clear image from forming on the retina. You hope that, by removing the cataract and replacing it with and IOL, the patient will have good vision after surgery. If the retina is healthy, then you should have good acuity. But if the retina is diseased and incapable of supporting good vision, then there's not point in doing the surgery. Interferometry "bypasses" the cataract by creating a pattern directly on the retina, so you can measure the potential visual acuity of the retina.

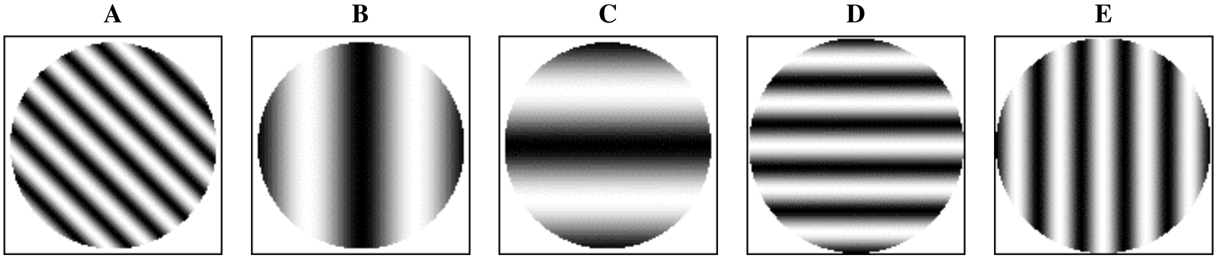
- The instrument projects two tiny point sources of light into the pupil, which creates a sine wave grating pattern on the retina.
- If you compare the light pattern in the pupil with the retinal image that the patient sees, you can observe the following: 1) The pattern on the retina is a sine wave grating. 2) The stripes are perpendicular to the line connecting the two dots. 3) When you increase separation between the dots, the stripes in the pattern become narrower. When the dots are close together, the stripes are broader.

  Q. How would you describe the relationship between the tiny dots in the pupil and the stripe pattern on the retina?
  A. They are Fourier transform pairs.

Sample test question from 2008 Exam 2

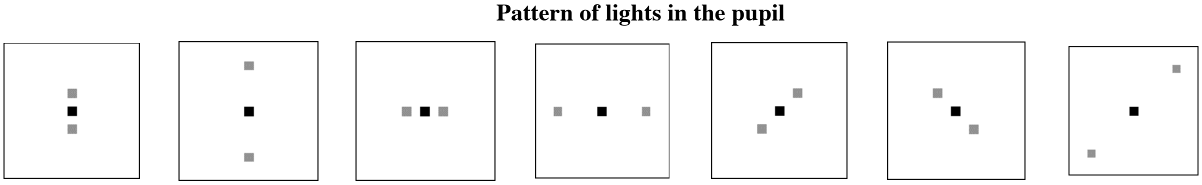
#24. The interferometer is used to measure a patient's retinal visual acuity behind a cataract. From the doctor side of the instrument you see three small lights in the patient's pupil. A sine wave grating is projected onto the patient's retina, which is the inverse Fourier transform of the pattern that the doctor sees in the pupil. The figures below show five sine wave gratings (A-E), followed by seven magnified images of Fourier spectra (1-7). Match the grating with its spectrum by writing the spectrum's number in the box below each grating. (5)

Pattern projected onto the patient's retina



A	B	C	D	E
7	3	1	2	4

Pattern of lights in the pupil



1	2	3	4	5	6	7