A look at Optical and infrared imaging systems

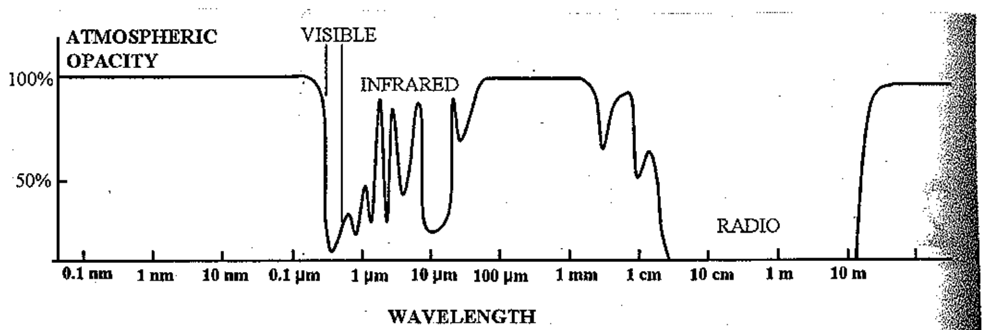


Figure 2.1. The transmission of the atmosphere at each wavelength from gamma rays to radio waves. Except for visible light, some near-infrared light, and radio waves, all other forms of electromagnetic radiation are blocked by the atmosphere.

Astronomy began with the Human eye in a small range of wavelengths.

- more classification-based, not statistically rigorous

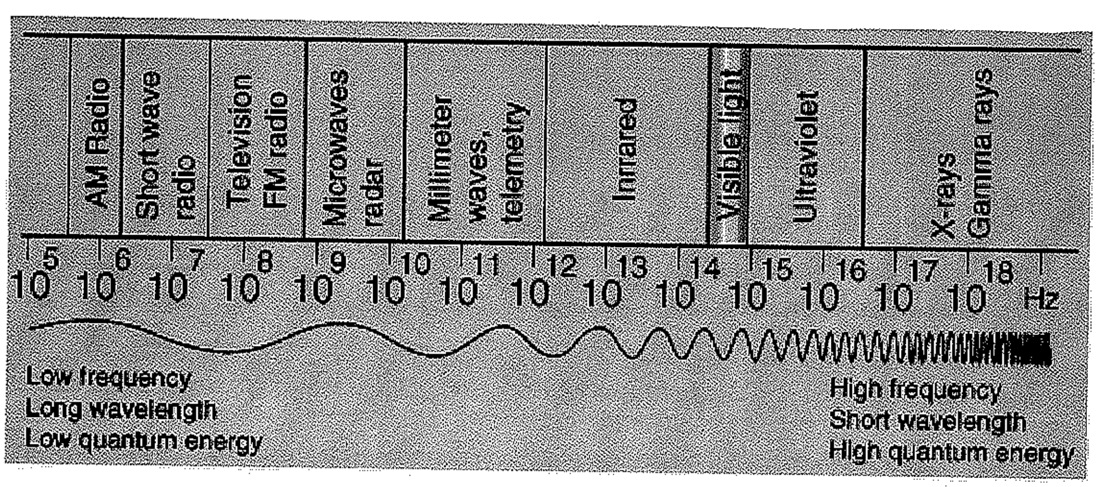
We see light roughly between 400 and 700 nm
"visible light"

$1 \text{ nm} = 1 \times 10^{-9} \text{ m}$
one-billionth of a meter

longer than ~ 1 µm is considered "infrared" up to about the mm scale

1 µm (pronounced 'micron') = 1×10^{-6} m

The electromagnetic spectrum from the Hyper Physics website:



Let's consider resolution first

for a 10m telescope, 600nm light (~red)

$$\frac{\lambda}{D} = \frac{6\times10^{-7}\,m}{10\,m} = 6\times10^{-8}\ rad.$$

example:

Alpha Centauri is ~4 Light Years away ~ 24×10^{12} miles

what physical scale is resolvable from this λ/D at Alpha Centauri?

$$6\times10^{-8}\,rad = \frac{x}{24\times10^{12}\,miles} \qquad x \sim 1.4\times10^{6}\ miles$$

1 Astronomical Unit (AU) = 93×10^{6} miles

AU = distance from Earth to Sun

How about strehl ratio?

$$S \approx e^{-\left(\frac{2\pi\sigma}{\lambda}\right)^2} \qquad \sigma \text{... wavefront error r.m.s.}$$

For good Strehl, e.g. $\sigma = \frac{\lambda}{20}$

(little defects on your mirror are $\sim \frac{\lambda}{20}$ in size)

$$\hookrightarrow S \approx e^{-(2\pi/20)^2} = 0.906$$

~ 90.6% strehl

this requires $\sigma = 25nm$ machining precision on your mirror at $\lambda \sim 500\,nm$

What if $\lambda = 10\mu m$? (10,000 nm) $\sigma = 10\mu m/20$

90.6% strehl requires 500 nm machining precision,

20X less precise.

For fun, if we use 25nm precision optics at $\lambda = 10\mu m$

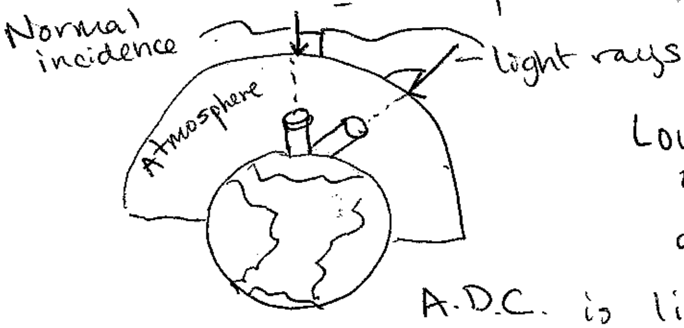
we'll have defects $\sim \frac{\lambda}{400}$ in size and strehl:

$$S \approx e^{-(2\pi/400)^2} = 99.98\%$$

Today optical imaging uses solid-state detectors

Components of a simple optical imager

- cooled CCD
- shutter (provide uniform exposure, etc)
- A.D.C - atmospheric dispersion corrector



Low angle on sky

↳ Non-normal incidence

acts like a prism, disperses light

A.D.C. is like an opposite prism, designed to correct this

- Any filters
- Etc.

Ideally CCD has uniform response, well behaved

But here are some common problems (outlined by Rieke):

- Intrapixel sensitivity is varied } Not as significant if image is well-sampled
- Gaps between pixels
- Fringing → layers of material on the detector
  ↳ interference between material

Rieke p.100:

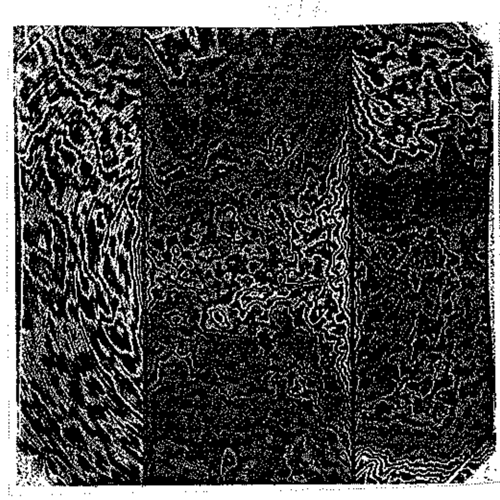


Figure 4.7. Fringing in a CCD at 0.95 μm. Image by Bryan Miller, credit Gemini/AURA, by permission.

- Hot/Dead pixels
- Non-linear response
- Persistence → latent image
  "memory of the image"
- Etc.

Good news: characterizing these effects allows us to remove them and see the real source response

Infrared Imaging (IR) ~1 μm – 200 μm

$1 \mu m = 1 \times 10^{-6} m$
(one millionth of a meter)

* IR camera demo

Visible light does not capture all phenomena
materials that transmit visible light may be opaque in IR, and vice versa

- the sun "burns" in visible light. cooler bodies will be detectable only in the infrared
- Peer through dust that is opaque in the visible
- see light reflected from heated dust in young solar systems and maybe even spot forming planets.
- Capture the older universe that is 'red-shifted' into the IR
- Etc.

The bright IR sky

OH emission in the atmosphere
↳ New tech: Bragg-grating fibers – literally cancel out the λ-specific lines (But there are so many lines)

"Chopping" – switch rapidly (10–20 times/s) between source and reference sky patch

the idea: (object + sky) ⟷ (sky) subtract the sky

Infrared Array Detectors

First photons must be converted into electric charges
- like CCDs, charge must be stored in each pixel
- transfer of charge in pixel
- Charges removed ∝ voltage, then digitized

• multiple 'outputs' to enable sky subtraction
• Pixel reset

High backgrounds require short exposures,
shutters are impractical
→ Exposure time controled by reset pulses & electronic read pulses
relative reset timing for each pixel must be known & consistent.

- Can read (non-destructively) immediately after reset and again after exposure time before reset.

McLean - Electronic Imaging ch. 11

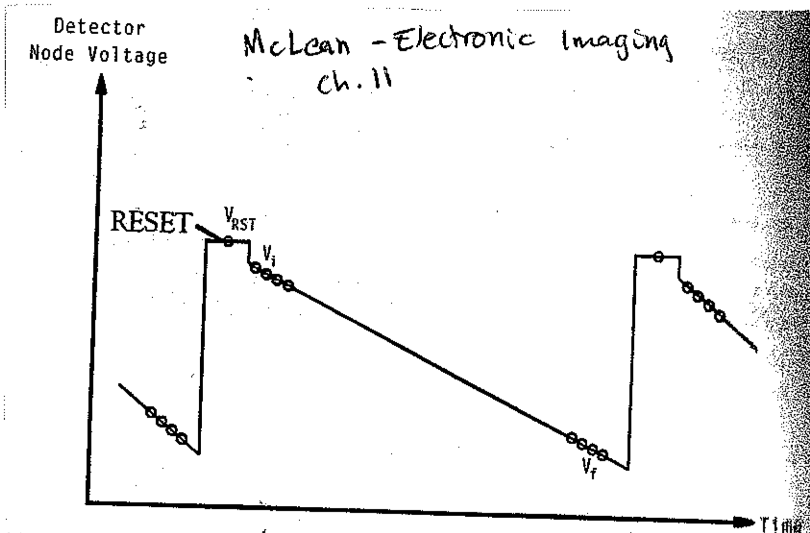


Figure 11.12. The schematic variation of the output voltage as a function of time for a typical pixel in an infrared array detector. Associated readout modes are described in the text.

or read / sample "up the ramp" – at regular intervals as the signal ramps up. Robust to detector saturation, cosmic ray events.

McLean ch. 11

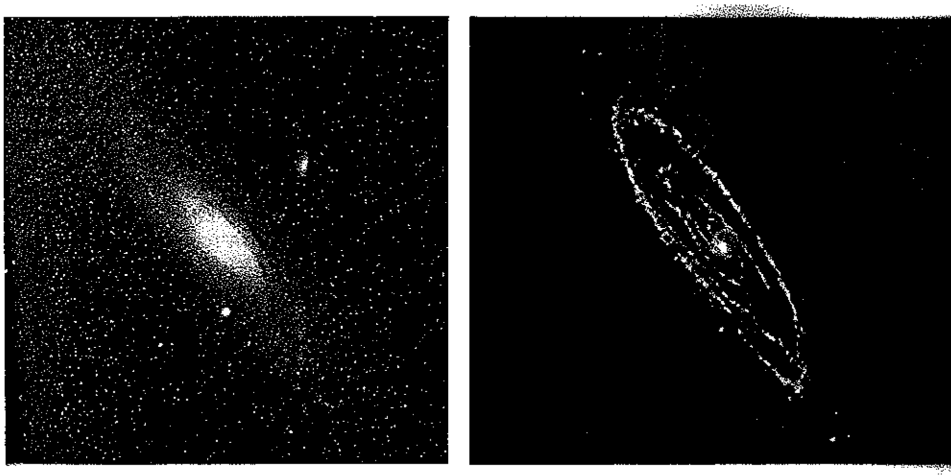
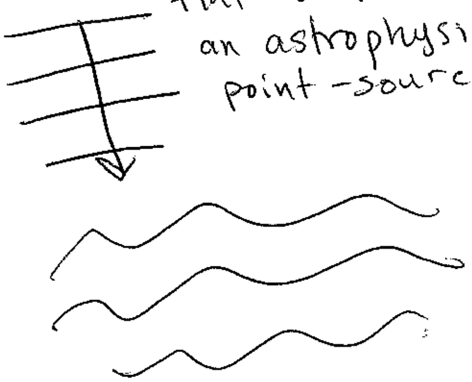


Figure 11.19. Two contrasting views of M31 (Andromeda galaxy) in visible and IR light. Credit: Spitzer Science Center

The payoff – a different view of the universe

Diffraction-limited imaging and the atmosphere

Reality:



flat wavefront from an astrophysical point-source

Amplitude variations: twinkling
Phase variations: changing refractive index

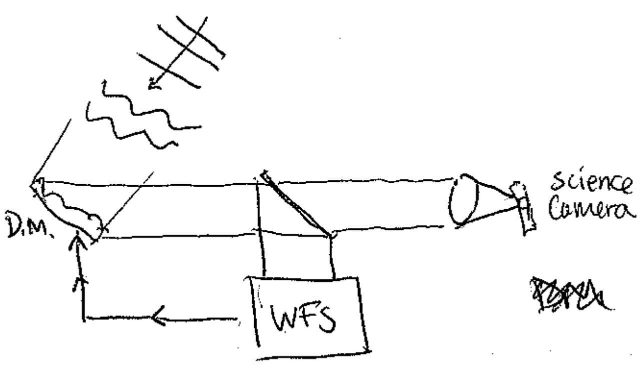
Earth's turbulent Atmosphere
- Wind patterns (time variation)
- Temp. difference btwn dome & outside
- Water vapor in air (like little lenses)

We can describe a characteristic size of turbulent cells (Fried parameter – r_0)
"length over which wavefront is not significantly perturbed"
e.g. $r_0 = 20$cm → resolution no better for a large telescope than a 20cm telescope
10m telescope is a waste for high resolution

Also, characteristic time $\tau_0 \propto r_0$
- Very short exposures can mitigate turbulence, but at the expense of imaging fainter objects.

Accd to theory (and practice) r_0 is larger @ longer wavelength

Besides space, how can we get diffraction limited images through the atmosphere?
→ correct the wavefront with <u>adaptive</u> <u>optics</u>



Requires:
- Deformable Mirror (D.M.)
- Ability to "sense" the wavefront
  wavefront sensor (WFS)
- Guide star (point-source) near target of interest
- Really fast control loop (communication between WFS and DM)