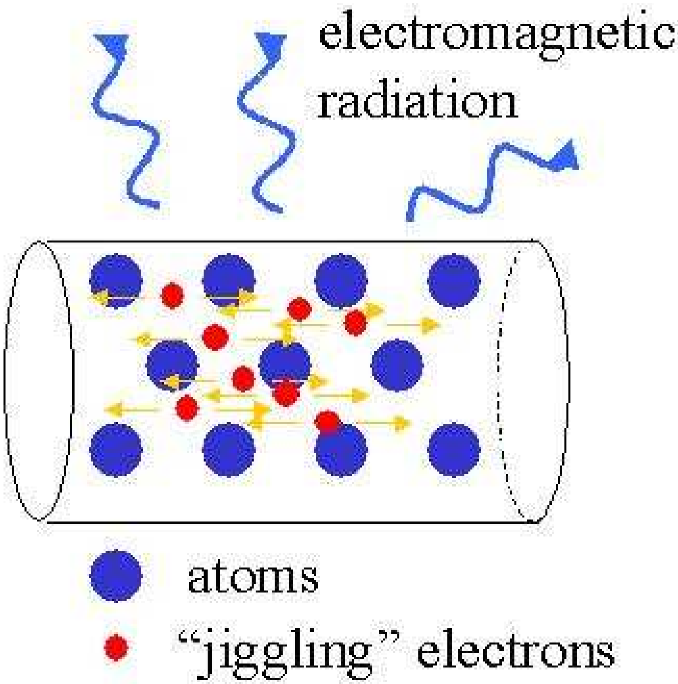
Usage of Electromagnetic Radiation

It is assumed that intelligent civilizations will communicate, at least in part, through electromagnetic radiation (electric and magnetic fields propagating in space). This is believed to occur due to the following reasons:

- Presumably these aliens are made up of atoms, forming into compounds. They almost certainly would find certain compounds to be "metals," hence extremely good conductors of electricity; all compounds are collections of positive and negative charges held within electromagnetic fields – "jiggling" collections of atoms will very easily produce electromagnetic radiation. Likewise, the detection



The "jiggling" of any charged particle emits radiation. Here, for example in a metal, alternating the voltage across the wire causes the electrons to move and the ions to remain motionless.

  of electromagnetic waves is natural – in that electromagnetic radiation will also induce charged particles to "jiggle" as well.

- Electromagnetic radiation (light) of certain frequencies propagate well in the vacuum of space – and they move at the speed of light ($c = 3 \times 10^8$ m/s, the absolute speed limit).

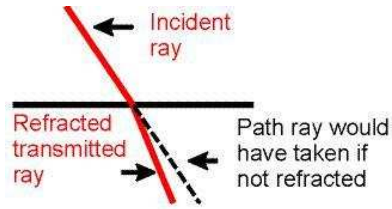
- Assume some civilization uses some other particles to communicate, such as neutrinos – that interact much less frequently than light does with ordinary matter. There are some problems that we see, for example, with using neutrinos as a communication medium:

- Since matter is so transparent to them, it is very hard to detect – much harder than normal electromagnetic radiation.
- They are only produced in nuclear reactions – even then, it is impossible (for us) to get a coherent signal from them.
- Particle processes that can convert light to neutrinos (and vice-versa) require thermal energies of 10 billion K or higher.

- Cheaper than sending matter through space across light-years.

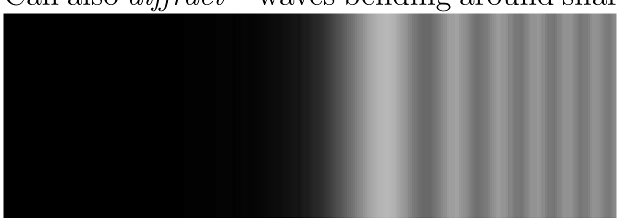
Basic Properties of Electromagnetic Radiation

- Light travels at the following speed of light $c = 3 \times 10^8$ m/s in a vacuum, with relation $\nu\lambda = c$, where ν is the frequency and λ is wavelength.



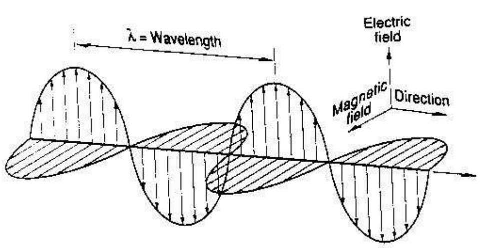
- Can refract (i.e. bend) when travelling from one medium to another.

- Can also *diffract* – waves bending around sharp obstacles and waves spreading around small openings.



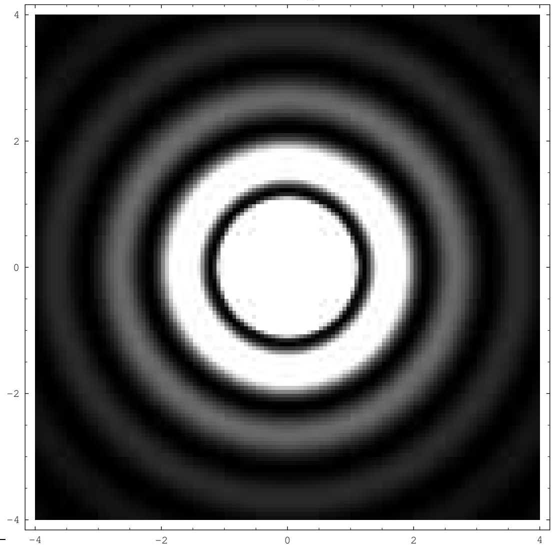
The properties of diffraction, which is dependent on both the wavelength of the light and the diameter of the telescopic device (can be optical telescope, radio telescope, anything that collects electromagnetic radiation).

- Light is also an electromagnetic wave with a specific polarization – usually given as the direction of the electric field as it propagates through space.



Diffraction-Limited Resolution of Telescopes

- All telescopes have a limited *angular resolution*, based on the wavelength of light being observed and the diameter of the telescope.



A point source emitting light at wavelength λ, as seen by a telescope of diameter D. The x and y axes measure angles in units of λ/D radians.

- A telescope can only resolve objects that are separated by angles greater than:

$$\theta_{\min} \approx \frac{\lambda}{D}$$

Because there is an angular "fuzziness" of λ/D due to diffraction of light particles collected by the telescope. This $\theta_{\min}$ is the *resolution* of the telescope.

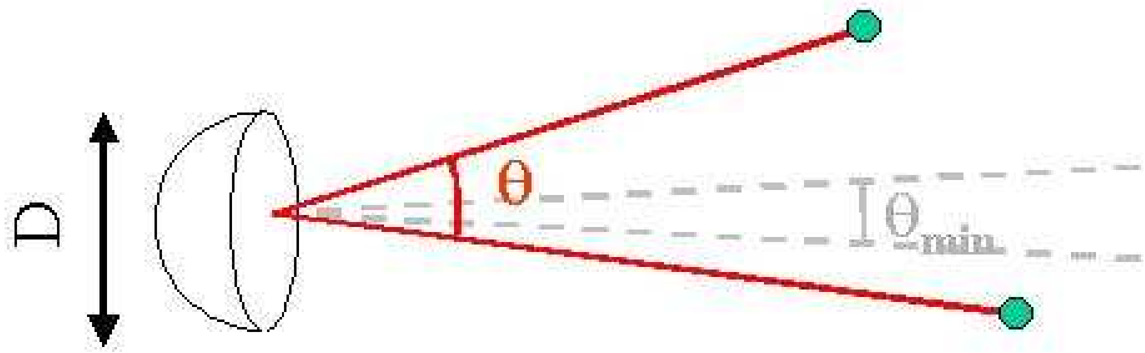
- Throughout this class, this resolution is due to the fact that the light undergoes *Fraunhofer diffraction*, which occurs when:

$$D^2 \ll \lambda R, \quad \text{or} \quad \frac{D}{R} \ll \frac{\lambda}{D}$$

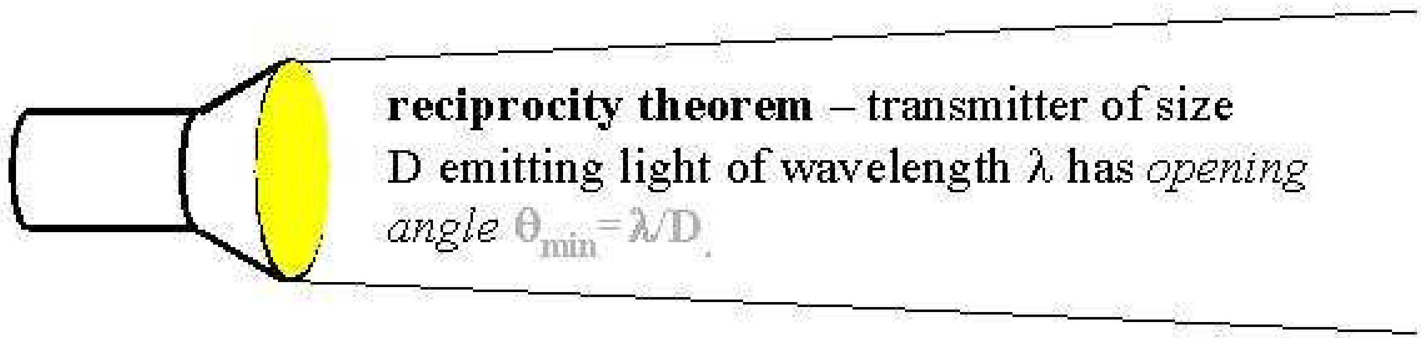
D – diameter of telescope; λ – wavelength of light; R – distance to source. Essentially, Fraunhofer diffraction for telescopes means that light waves travel in parallel up to the telescope to a greater "straightness" than the angular resolution of the telescope.

- Now according to the **reciprocity theorem** a detector of diameter D detecting radiation of wavelength λ can be replaced by transmitter of size D – resulting in angular size of transmission $\theta \approx \lambda/D$.

Diffraction Limits to Detectors, & Detectors ↔ Transmitters



If compact objects (such as stars) are separated by angle θ > θ_{min}, then the separate stars can be resolved. Recall that $\theta_{min} = \lambda/D$.



reciprocity theorem – transmitter of size D emitting light of wavelength λ has *opening angle* $\theta_{min} = \lambda/D$.

some EM transmitter

Transmission of Signals, Noise, etc.

First consider the fact that for a signal to be processed at a rate of N bits per second, one requires a *bandwidth* (the frequency range of your signal) of approximately N Hertz – this is due to the fact that each "bin" (corresponding to where you put your bits) is 1 Hz in size. There are some issues associated with bandwidth: [1]

- The strength of a detectable signal (radio, optical, whatever) decreases as the bandwidth increases.
- One could send the same amount of information (in bits) over a longer period of time – the number of bits required per second decreases, so the bandwidth also decreases.
- Each "bin" must be 1 Hz wide, and store the separate bits. But why can't the bins be, say, 0.5 Hz wide? This goes to the concept of "beats" between two waves of roughly the same frequency. The beat frequency = $\Delta\nu$ (the difference in frequency). Thus, bins separated by 0.5 Hz perform a "beat" every 2 seconds, so the information content is half that at 1 Hz.
- Generally speaking – doubling bandwidth → doubling information transfer rate.
- Furthermore, it is generally a "bad" idea to have a bandwidth $B \sim F/2$ (where B is the bandwidth in Hz and F is the carrier frequency in F) – the signal becomes completely unresolvable beyond this. This implies that **higher frequency radiation is a better source of information, because it allows for a higher bandwidth**.
- The description I have shown here – uniform bins (or often referred to as *uniform sampling*) – is not the end of the story. If you want to be fancy, and take into account the total nonredundant information content (i.e. signal compression) in a signal, you can perform nonuniform sampling (frequency bins of different sizes) or at least a much smaller bandwidth.
- For SETI (search for extraterrestrial intelligence), since we don't "know" the signal, then it probably makes sense to have uniform sampling of our signal – **no signal compression or lossy signal (i.e., MPEG or JPEG)**.

[1] Look to the section on the Fast Fourier transform – transforming your time-resolved data into a frequency spectrum – in *Numerical Recipes* at http://www.nr.com, or in Horowitz and Hill's *The Art of Electronics* – just ask any electrical engineering major or electrical engineer or anybody who does anything with electronic devices.

BAD IDEA FOR SETI – NO LOSSY OR COMPRESSED DATA SUCH AS MP3

Bandwidths of Typical Signals

Source	Frequency Range	Bandwidth
AM Radio	530 - 1605 kHz	10 kHz
FM Radio	88-108 MHz	150 kHz
UHF TV (picture)	470-806 MHz	6 MHz
Audible sound	NA	20 kHz

Here I put NA for "Audible Sound" because encoding sound that we hear at our natural rate would require a bandwidth of 20 kHz. However, supposedly this signal would be carried at some central frequency (optical or radio, or in the form of *pulsed signals* in telephone wires).

Signals, Noises and the "Unambiguous" Determination of a Signal

- Of course, we cannot **unambiguously** determine a signal – we can only do this to a level of certainty such that a false result is vanishingly improbably (or at least *very improbable*).

- Suppose our "noise" is white – random, completely uncorrelated noise (that is, a given noise signal at time T will have zero predictive value on the noise signal at some later time). Now given the signal-to-noise ratio $SNR = S/N$, the *error rate* of information is given by:

$$\epsilon = \frac{1}{\sqrt{2\pi}} \int_{SNR}^{\infty} e^{-x^2/2}\, dx$$

  For $S/N = 2.0$, the error rate is 2.8%; for $S/N = 1.0$, the error rate is 15.9%. And it gets worse as the SNR gets lower. (I can prove this if anyone wants a proof of this – given the above probability, think of how often one can get false positives).

- For comparison, the human eyes and ears have trouble discerning inputs where $S/N \ll 100$ (example – have you ever tried to hear a scratchy, hissing speaker or a "noisy" TV?).

- Noise level can be controlled through the following methods:
  - The noise level goes down as $\sqrt{\text{number of noise signals received}}$, so averaging over longer times allows for the determination of a signal, but it comes with downsides – destruction of all information received in shorter times. Suppose the "integration time" (the time required to average the signal to make the SNR acceptable) is τ. Then the effective bit-rate becomes $1/\tau$.
  - Reduce the "noise temperature" T_N of the detection equipment. This has a formal definition (which I will not deign to demonstrate) – suffice to say that the power level of noise becomes:

$$P_{\text{noise}} = kT_N B$$

    Where B is the bandwidth.

    Typical noise "noise temperatures" of devices, esp. radio devices, is approximately 10-15 K, down from few thousand (2000-3000 K) in the 1960s.

– Look in parts of spectrum that have relatively low noise levels. Just some examples of the sources of noise. Examples of noise from the environment include:

  * radio noise – TV, radar, commercial radio stations, any type of electrical industrialized activity that emits at high frequencies (spark plugs, microwaves, etc.)
  * H_2O, CO_2, other gases which absorb much of radiation in the infrared.
  * Milky Way – pulsars, supernovae, interstellar medium, etc., which produce radio emissions (require the presence of plasma in most cases).
  * continuum noise from the Big Bang – the 3 K background temperature peaks in the microwave.
  * quantum noise, arising from the particle-like nature of light.

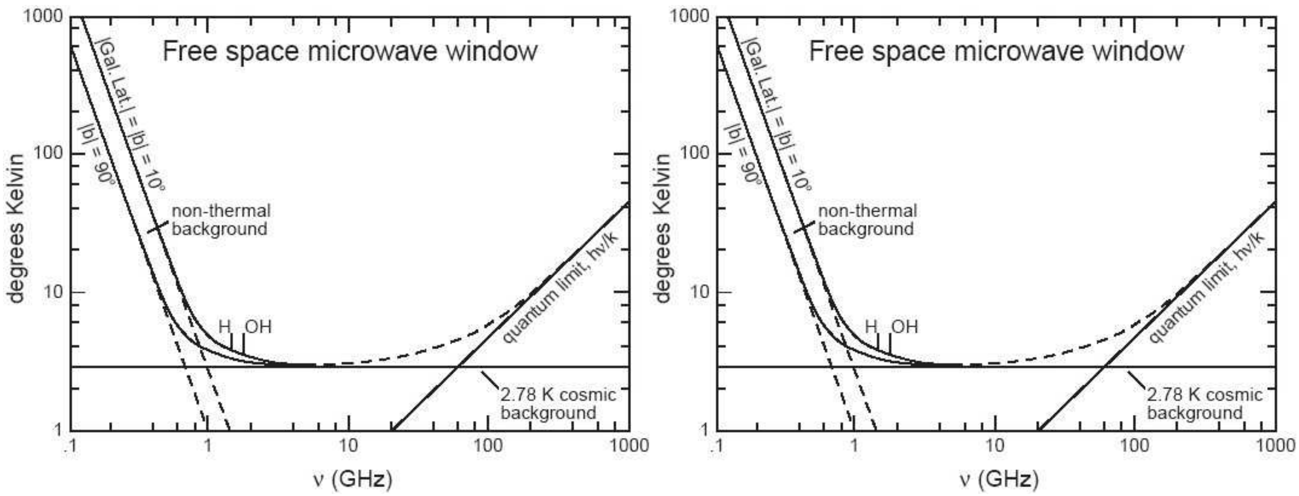


Diagram showing the effective noise temperature at various radio and infrared frequencies, from space (on left) and from Earth's surface (on right). The noise temperature is minimized about the "water hole" (resonant radio emissions from H_2 and OH^-). Quantum noise, whose temperature $T = h\nu/k_B$, where k_B is Boltzmann's constant, only contributes to the higher frequencies in space. These plots are taken from Bernard M. Oliver, *Acta Astronautica* **6**, 71 (1979).

Economic Arguments for Large Transmitters and Minimal Bandwidths

Regardless of how the power from a given transmitter (optical, radio, etc.) is distributed, the signal strength S in terms of distance D and available transmitter power goes as:

$$S \propto \frac{P}{D^2}$$

And the number of civilizations reached goes as:

$$N_D \propto D^3$$

In a problem such as this, one has a minimum threshold signal S and a given power P of the transmitter $\rightarrow$ solve for $D \rightarrow$ solve for N_D.

Now suppose we have **half** the resources, so the power per transmitter is half. Then the distance at which the signal is heard:

$$D' \propto \sqrt{\frac{P/2}{S}} = D/\sqrt{2}$$

The number of civilizations reached becomes:

$$N'_D \propto 2\left(D'\right)^3 = \frac{2}{2^{3/2}} N_D = N_D/\sqrt{2}$$

So dividing the power of transmitters, *keeping all other things equal*, is not economical.

An important measure of the strength of a signal *from which one wishes to extract usable information* is the signal per unit bandwidth:

$$S_{\max} \propto \frac{P_{\max}}{D^2 B}$$
$$D \propto \sqrt{\frac{P_{\max}}{S_{\max} B}}$$

Other Examples of Communication