LECTURE 1: INTRODUCTION

> Space instruments are the links between:
- target
- missions
- data users
- spacecraft
- ...

> Two groups:
1. Remote — telescopes, imagers, radar, ...
2. In situ — magnetic field, gravitational field, ...

> A space experiment is:
- to realize an experiment outside Earth
- observation of the Universe

> Types of scientific space missions:
1. Earth observation
2. Astrophysics
3. Planetary Science
4. Heliophysics

> We go to space because:
1. Some things can't be done from Earth
2. Unique environment
3. pushing innovation
4. ...

> The atmosphere absorbs certain λ of the EM spectrum. This creates atmospheric windows

> The EM spectrum: shorter λ ⟵ ⟶ longer λ

> Challenges:
1. Go + Stay + Return
2. Cost
3. Harsh environment
4. ...

> Observables:
1. EM waves
2. Static fields
3. Particles
4. Matter samples
5. Gravitational waves

> Instruments act as an information filter because they do not capture all of the information that exists (e.g. only a certain λ)

> The mission design process consists of:
1. Mission analysis — 0
2. Feasibility — A
3. Preliminary definition — B
4. Design — C
5. Production — D
6. Operation — E
7. Disposal — F

> The TRL is a number associated with something which tells how far into development it is

↳ Range : 1 (basic principles) → 9 (flight proven)

> A payload is those elements dedicated to producing misson data and sending it back

LECTURE 2: ELM - SENSING THE BASICS

> The cells in a scientific image is relative to the position on the detector, and the value corresponds to the number of received photons

> The field of view is the angle of observation
> The projected area on the ground is the swath
> The resolution indicates the smallest feature that can be observed
> The sharpness describes how well edges are perceived
> The contrast is the difference between light / dark

↳ These five are indications of the image quality

> All objects can be observed by use of photons

↳ we do so from space mainly to get rid of the atmosphere

↳ we can get:
- Temperature
- Composition
- Motion
- ...

> Photon generation / absorption processes:
① Black body radiation
② Quantum transition
③ Acceleration of charged particles
④ Annihilation of (anti) matter

① ↳ BB radiation is most fundamental source of radiation

↳ $L_\lambda(T) = \frac{2hc_0^2}{\lambda^5}\left[e^{hc_0/\lambda k_B T} - 1\right]^{-1}$

↳ Wien: $\lambda_{max} = \frac{b}{T}$; $b \simeq 0.028$

> EM radiation is quantified

↳ $E_\nu = h\nu = hc_0/\lambda$

② ↳ Absorption causes an electron to move to an excited state with energy level:

↳ $\Delta E = h\nu = E_1 - E_0$

> Spontaneous emission is the opposite

> Stimulated emission is when incoming radiation causes a drop down

> A light source is a geometrical element out of which light escapes

↳ It can be from production, reflection, scattering

> Light can be seen as: ① Ray
② Wave
③ Particle

Light as a Ray

> Laws for geometrical optics: ① Reflection
② Refraction
③ Diffraction

① ↳ $\theta_i = \theta_r$

② ↳ $n_1 \sin\theta_i = n_2 \sin\theta_t$

③ ↳ $\sin\theta_{diff} \pm \sin\theta_i = \frac{m\lambda}{\Lambda}$

> Scattering is a deflection not following reflection or refraction

↳ $TIS \approx \frac{4\pi R_q}{\lambda}$

> The index of refraction is a function of the wavelength

↳ This causes dispersion

↳ $\lambda_n = \frac{v}{f} = \frac{c}{nf} = \frac{\lambda}{n}$

> The optical path length is the length that light needs to travel through vaccum to create the same phase difference

↳ $\delta(\lambda) = n(\lambda) \cdot l$

> Fresnel reflection is the reflection at the boundary of 2 media

↳ Reflectivity $= \frac{I_r}{I_0} \cdot 100\%$

↳ Transmitivity $= \frac{I_t}{I_0} \cdot 100\%$

↳ The process depends on the polarization, and we get r_s, r_p, t_s, t_p

> In total we have 3 processes: ① Reflection
② Transmission
③ Absorption

↳ The Beer-Lambert law: $T = \frac{I_t}{I_0} = e^{-\alpha}$

↳ Conservation of energy: $R + T + A = 1$

Light as a Wave

> Maxwell equations give a wave equation

> The Huygens principle states that every point on a wave acts as a point source

↳ Each point source creates a spherical wave of radius $r = v \cdot t$

↳ Rays are perpendicular to the wavefronts

↳ The Huygens principle explains diffraction, the bending of waves behind an obstacle

↳ The double slit experiment confirms it, making interference patterns

> In thin films, waves can also reflect

> Anti-reflective coatings are needed to avoid parasitic reflections

LECTURE 3 : IMAGERS

> Earth observation is the gathering of information about the Earth

↳ Imagers can be used

> The general concept of imagers is to collect photons (→ telescope assembly), focalize them to a detector and converting to electrons (→ detector), and numerize it for data storage and transfer → camera

> To create optical space instruments, we need:
① Radiometric budget
② Optical system
③ Detector system

> The resolution is the ability of an optical system to return the information contained into an optical scene

↳ Types:
① Spatial / Resolving Power — distance
② Radiometric — photons
③ Spectral — wavelength
④ Polarimetric — stokes vector

Paraxial Optics

> A lens has the properties:
① f
② R_1
③ R_2
④ d
⑤ n

↳ Lensmaker's equation: $f^{-1} = (n-1)\left(R_1^{-1} - R_2^{-1} + \frac{(n-1)d}{nR_1R_2}\right)$

> Paraxial optics is used for image formation and size magnification, not quality

> Rays remain close to the optical axis

↳ $\sin\theta \approx \theta$; $\tan\theta \approx \theta$

> Can determine:
① Location of object / image planes
② Clear aperture
③ Optical power
④ Magnification
⑤ Separation
⑥ Radiometric calculation

↳ Analysis of optical aberration is required for image quality

> The paraxial approximation basics are:

① Geometrical optics domain

↳ λ is small compared to objects ⇒ light is a ray

② Optical path depth

↳ $\delta = \int_A^B n(s)\,ds$

③ Fermat principle

↳ Light chooses the path which minimizes the time to go from point A to point B

④ Stigmatism

↳ The image of a point is a point

> For image formation with a lens, a graphical paraxial ray trace gives 3 rays:

① Parallel to optical axis
② Passing through the center
③ Passing through the object focus

> Magnification:

① Transverse

↳ $m = g_y = \frac{\overline{A'B'}}{\overline{AB}} = \frac{y'}{y} = -\frac{d_i}{d_o}$

② Axial

↳ $m = g_z = \frac{\Delta z'}{\Delta z} = g_y^2$

> A virtual image is an image through which light does not go

> A real image is the collection of focus points made by converging rays, while a VI is the collection of focus points made by extensions of diverging rays

> Thin lens equation: $d_i^{-1} + d_o^{-1} = f^{-1}$

↳ $m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}$

> For a source located at infinity, all rays can be considered parallel

↳ For an extended source, the information is angular

↳ Optical systems convert angular into a spatial information

↳ $x = f \tan\theta$

> The ground sampling distance is the size of a projected pixel

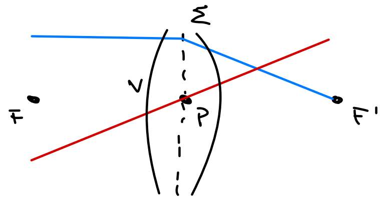
> The spatial resolution is the smallest ground feature that can be resolved
> The swath is the total ground width captured by the FOV

↳ $\frac{GSD}{h} = \frac{PS}{f} = \tan \alpha$

> As a spacecraft orbits, it covers one direction of motion. To scan the ground, a 1D sensor can be used

> An optical system can be replaced by its cardinal points and planes

① Focus F
② Principal point P
③ Principal plane Σ
④ Nodal points P
⑤ Thin lens limit V



> The optical power

↳ $\varphi = (n-1)\left(C_1 - C_2 + \frac{n-1}{n} t\, C_1 C_2\right)$

> Two rays describe a system: ① Chief — Edge → center
② Marginal — Center → Edge

> The entrance pupil is the image of a stop upstream
> The exit pupil is the image of a stop downstream
> The aperture stop is the physical aperture that limits the bundle of rays

> A field stop limits the angular size of an object

> The F-number is the ratio between the focal length and the entrance pupil

↳ Impacts the diffraction effect on the focal plane

> The spectral domain is determined by: ① Source
② Transmission
③ Detector
④ Polarization

Aberration

> Aberrations are deviations from the paraxial ray trace

↳ Depends on: ① Optics shape
② Fields
③ Wavelength
④ Aperture size

> Chromatic effects happen because of varying n with λ

> Third order aberration happens due to the small angle approximation

> Spherical aberration (on axis) is due to a spherical shaped optical surface

> Astigmatism is a form of off axis aberration

> Due to wave properties and aberration, the image of a point is not a point

> Airy function: $r = 1.22 \frac{f\lambda}{D} = 1.22 \, F\# \, \lambda$

> The Rayleigh criterion states that two points are considered resolved if the maximum of one is not closer than the first minimum of the other

> The point spread function is a 2D distribution of light intensity

↳ $S_i(e) = e * h_i$

> The modulation transfer function indicates the ability of an optical system to transfer the frequency information

↳ The optical transfer function is the Laplace transform of the PSF

↳ $OTF = MTF \, e^{i \, PSF}$

LECTURE 4: OPTICAL COMPONENTS

> In general, a lens works by the Snell-Descartes law

↳ $n_1 \sin\theta_1 = n_2 \sin\theta_2$

> For an incident collimated beam, we can draw out a selection of rays, and find they come together at some point, the focal point

↳ Simplified: use Lensmaker formula

↳ Based on basic ray tracing

> For more than 1 λ, we have aberration happening

↳ This gives multiple focal lengths (1 per λ)

↳ f increases with λ

↳ To solve, we can add a compensating lens

↳ For lens combination:

↳ $f_{eff}^{-1} = f_1^{-1} + f_2^{-1} - \frac{d}{f_1 f_2}$

↳ We thus use 2 different materials to compensate dispersion

> Note that no lens is 100% achromatic

↳ Because of this, in space often mirrors are used

↳ Different shapes are used:
1. Flat
2. Spherical
3. Parabolic
4. ...

> For a spherical mirror: $f = -0.5 R_c$

↳ For small f/d_{beam}, the outer rays do not have the same f

↳ This is spherical aberration, and why we use other surfaces

↳ Parabolic mirrors have a single focal point

> Other reasons for mirrors:
1. Segmented / Folded is space proof
2. Coatings can be adapted

Materials

> A material is not transmissive in the entire EM spectrum

↳ $n = \eta + i\kappa$, with κ the absorption coefficient

↳ For the electric field:

↳ $E = E_0 e^{iknz - i\omega t} = E_0 e^{-k\kappa z} e^{ik\eta z - i\omega t}$; $k = \frac{2\pi}{\lambda}$

↳ Decrease due to absorption

↳ Intensity:

↳ $I = |E|^2 = |E_0|^2 e^{-2k\kappa z} = I_0 e^{-2k\kappa z}$

> Different materials can be chosen for transmissive optics, depending on bandwidth, availability, budget, and desired application

> For reflective optics, most of the shape is given by the substrate attached to the mount

↳ It is submitted to σ and ΔT which put requirements on it

> Coatings inherit the deviations of the substrate

> Metallic coatings are for broadband reflection
> Dielectric coatings are for specific bandwidths

> Reflection happens in transmissive optics (Fresnel)

↳ To find the transmitted field, we look at reflection at the interfaces, and absorption in the medium

> Parasitic reflection is when part of the incident signal is reflected

↳ This causes less signal on the detector, and the possibility of a fake signal ghost

↳ To reduce the effect, anti-reflective coatings can be used

↳ They work by adding a layer which creates a second reflection which cancels the first destructive interference

↳ $\Delta\varphi = \pi$

↳ Thumb rule:

↳ $n_{coating} = \sqrt{n_{air} n_{sub}}$; $h \sim \frac{\lambda}{4}$

Polarization

> Light consists of: ① Electric field
② Magnetic field

↳ The two fields are perpendicular to each other and the propagation direction

> Polarizers select only one type of polarization and change the intensity of light
> Birefringent plates change the polarization state

> Polarizers are characterized by: ① Transmission axis
② Absorption axis (⊥)

↳ Only the vibration parallel to the transmission axis is transmitted

↳ $\vec{E}_{out} = \vec{E}_{in} \cos\theta$; $I_{out} = I_{in} \cos^2\theta$

> Polarizers by absorption have long molecules inside which absorb the parallel vibration

↳ This results in linearly polarized output in direction of transmission axis

> A birefringent component has anisotropy in the crystal, and presence of 1 particular direction inside the component optical axis

↳ Light experiences 2 non-parallel resistances: ① Strong bonds
② Weak bonds

↳ We get 2 speeds in the material

↳ $\Delta n = |n_o - n_e|$; $n = \frac{c}{v}$

↳ The optical axis is parallel to the interface

↳ After the plate, there is a shift between the states

↳ $\Delta x = d(n_o - n_e)$

↳ This creates a phase shift

↳ $\Delta\varphi = \frac{2\pi}{\lambda_v} \Delta x$

> Other polarization effects: ① Reflection
② Dichroism
③ ...

Diffraction Gratings

> Diffraction gratings are repetitive arrays of diffractive elements (apertures or obstacles) that result in periodic alterations in phase, amplitude, or both of an emergent wave

> Looking at narrow slits with normal incidence, using the Huygens principle and interferometry, we get that each slit acts as a point source, and each sub-source emits several rays

↳ Each set of parallel rays recombines to make an equivalent wavefront

↳ There is a phase difference:

↳ $\Delta x = d\sin\theta = m\lambda$

↳ For normal incidence, 1 beam is split into several beams

↳ For polychromatic, 1 beam is split along the period

↳ For non-normal, the working principle is the same

> Amplitude grating causes periodicity realized by a succession of opaque and transmissive area

> Phase grating causes periodicity realized by a variation of phase, and with that of optical path

> Diffraction grating can happen with transmission and reflection

> Used for spectroscopy to split the light by λ

Optical Filters

> Types: ① Short pass
② Long pass
③ Bandpass
④ Notch
⑤ Neutral densities

① ↳ High transmission at low λ, low transmission at high λ

② ↳ Low transmission at low λ, high transmission at high λ

③ ↳ Only transmits a certain bandwidth

④ ↳ Only blocks a specific bandwidth

⑤ ↳ Constant attenuation for large bandwidth

↳ Avoid detector saturation

LECTURE 5: RADIOMETRY

> Transmittance and throughput need to be considered before building an instrument to evaluate the number of photons reaching the detector

↳ Too few photons → low SNR (or no signal at all)
↳ Too many photons → saturation and possibly destruction of the detector

> The system spectral transmittance is:

↳ $\tau(\lambda) = \frac{P_{out}(\lambda)}{P_{in}(\lambda)}$ [-]

↳ P_{out} is the spectral radiant power at the focal plane
↳ P_{in} is the spectral radiant power falling in the entrance aperture

↳ Determined by: ① Spectral transmittance, ② Spectral reflectance, ③ Spectral absorbance } of each optical element

↳ $R(\lambda) = \prod R_i(\lambda)$; $T(\lambda) = \prod T_i(\lambda)$

> There is a source of EM waves/photons → Losses → Gathering → Spectral filter → Detector

> In addition to image quality, the amount of light reaching a detector is important

> A beam can be defined by two elements of area:

↳ This is the locus of possible rays that pass through the two areas separated by a distance d

↳ Each ray is defined by a vector and transports energy

> A point source is a small source of light that radiates equally in all directions

↳ $h_x h_y << R^2$

> An extended source is any source having measurable dimension

> Angles: ① Plane • $\varphi = \frac{S}{R}$ [rad]

② Solid • $\Omega = \frac{A}{R^2}$ [sr]

> The F-number • $F\# = \frac{f}{D} = (2\sin\Theta_{1/2})^{-1}$

> The numerical aperture is a dimensionless number characterizing the range of angles accepted by the system

↳ $NA = n \sin \theta_{1/2}$

↳ $\Omega = \frac{\pi}{4(F\#)^2} = \frac{\pi (NA)^2}{n^2}$

Radiometry of Point Sources

> The luminosity or radiative flux/power ϕ_e is the amount of energy per unit of time leaving the source

> The point source or radiant intensity I_e is the power per unit solid angle

↳ $I_e = \frac{d\phi_e}{d\Omega}$

> The irradiance E_e is the illumination by a point of a surface placed at a distance R

↳ $E_e = \frac{\phi_e}{A_i}$

> Considering an isotropic emission of a point source:

↳ $I_e = \frac{\phi_e}{\Omega}$

↳ At a distance R_i:

↳ $E_e = \frac{I_e}{R_i^2}$ inverse square law

↳ Trajectory is spherical, but most surfaces are flat ⇒ correction needed

↳ If $A \perp R$, A' as θ with radius, then $R' > R$ and $A' > A$

↳ $E_e' = \frac{\phi_e}{A'} = E_e \cos^3 \theta$

Radiometry of Extended sources

> For extended sources, there are some degrees of variation in the amount and direction of emission and with position

> The radiance or brightness $L_e = \frac{\phi_e}{A_s \Omega}$

> An extended source can be seen as an area with a large collection of point sources distributed uniformly

↳ If each ΔA contains a point source with an I_e constant in all directions, the brightness of the sources in a normal direction is:

↳ $L_e(0) = \frac{\phi_e}{\Delta A \Omega}$ → At an angle: $L_e(\theta) = \frac{L(0)}{\cos\theta}$

> A Lambertian source can be used as an approximation

↳ $I_e = \frac{\phi_e}{\Omega} \cos\theta$; $L_e(\theta) = L(0)$

In Optical System - Point Source

> Behind the optical system exists another point source, the image

> From conservation of energy:

↳ $\Phi_e = \frac{I_e A_1}{t_0^2} = \frac{I_e' A_1}{t_1^2}$; $I_e' = I_e \frac{t_1^2}{t_0^2} = M^2 I_e$

↳ M: transverse magnification of the system

> Entrance and exit pupils are important for calculating radiometry

In Optical System - Extended Source

> In the image space the observer sees an image if light is redirected

> For passive components:

↳ $\Phi_e' = T \Phi_e$

↳ T: Transmittance of the system

> We can obtain the Etendue law:

↳ $A\Omega = A'\Omega'$

↳ $L_e' = T L_e$

↳ Etendue ($A\Omega$) is conserved (aka area-solid angle conservation)

Pupils and Apertures

> Finite nature of lenses and mirrors induces that they collect only a fraction of the energy emitted by a point source → clear aperture

> Any element that limits the amount of light reaching the image plane is an aperture stop

↳ Limits the light gathering capabilities

> A field stop determines the FoV of the instruments

> Pupils determine whether or not a given ray will go through the entire optical system and reach the focal plane

> The image of the stop is seen from an axial point

↳ In object space: entrance pupil

↳ In image space: exit pupil

Photon Noise

> Photon noise is the result of the discrete nature of the radiation

↳ Poisson distribution describes the probability:

- $p(i) = \frac{s^i}{i!} e^{-s}$

- From that:
  - $\sigma_s = \sqrt{s}$
  - $SNR = \frac{s}{\sqrt{s}} = \sqrt{s}$

LECTURE 6: SPECTROSCOPY

> Spectroscopic information is the decomposition of light on a spectrum

> Spectroscopy is the study of physical phenomena over a frequency spectrum based on a wave process

> Each material has its own unique set of spectral lines

↳ Emission/absorption are the basis of spectroscopy

> Schrödinger's Equation:

↳ $i\hbar \frac{\partial}{\partial t} |\psi(t)\rangle = \hat{H} |\psi(t)\rangle$ $\hbar = \frac{h}{2\pi}$

↳ If H is independent of time → stationary solution

↳ Separation of time dependent solutions and space:

↳ $\psi(\vec{r}, t) = \psi(\vec{r}) e^{iEt/\hbar}$

↳ $H\psi = E\psi$ time-independent Schrödinger Equation

↳ Solutions are a set of ψ_n associated with state energy set E_n

> Lecture 2 gave definition of absorption and (stimulated) emission

> A spectral line extend over a range of frequencies

↳ g_i correspond to degeneracy of the energy levels

↳ Degeneracy: one single value of E, while multiple λ

↳ The center may be shifted from its nominal central λ (Doppler shift)

↳ Reasons of broadening: ① Thermal Doppler
② Natural
③ Pressure / Collisional

Molecular Spectra

> The complexity increases with many-atom systems:

① Broken symmetry: ⓐ Atom: spherical symmetry
ⓑ Diatomic: in-line symmetry
ⓒ Other: More complex

② Quantum transitions involve rotations and vibrations

③ Orbitals for electronic transitions are built differently

↳ There are group vibrations

> We have:

↳ Energy $\Delta E = h\nu = \frac{hc}{\lambda}$

↳ Wave number $\sigma = \frac{1}{\lambda} = \frac{\Delta E}{hc}$

> The electronics, vibrational, and rotational energies are independent

↳ $E = E_{el} + E_{vib} + E_{rot}$

↳ $\psi_{tot} = \psi_{el} \cdot \psi_{vib} \cdot \psi_{rot}$

> A change of E_{tot} is then:

↳ $h\nu = hc\sigma = \Delta E = E' - E'' = \sum E_i' - E_i''$

> For an electronic transition, there is a general structure
> For a vibrational transition, there is a coarse structure
> For a rotational transition, there is a fine structure

Spectroscopic Instruments

> A spectroscopic instrument is a scientific instrumet used to split the light into an array of separated colors → spectrum

↳ A spectrum shows the intensity of light in function of λ and f

↳ light deflection and separation is produced by a Prism or diffraction grating

> A spectrometer consists of: ① Dispersion element
② Pupils (from stops)
③ optical interfaces

Additional Subtilities

> A slit can be added at the entrance and exit

↳ $\tan \theta_{col} = \frac{S_i/2}{f_{col}} = \frac{S_e/2}{f_{col}}$

↳ The intensity profile shows the transmission through the slit for each λ

> A prism causes diffraction as seen before

↳ $n(\lambda) \Rightarrow \theta(\lambda)$

> Grating also results in diffraction

↳ $\sin \theta_{diff} \pm \sin \theta_i = \frac{m\lambda}{\Lambda}$

↳ Different gratings exist: ① Sawtooth
② Sinusoidal
③ Laminar
④ Phase

↳ The diffraction efficiency is given by:

↳ $\eta^m(\lambda) = \frac{I^m(\lambda)}{I_0(\lambda)}$

> The diffraction of a laser spot by a circular aperture is an Airy disk

↳ The angle at which the first minimum occurs:

↳ $\sin\theta \approx \theta \approx 1.22\frac{\lambda}{d}$

↳ The resolution is limited due to the diffraction of light

↳ with an aperture w_i of finite size, we are diffraction limited

↳ $D_{Airy} = 2.44 \frac{f_{foc}\lambda}{w_i}$

↳ linear dispersion $= \frac{\Delta\lambda}{\Delta x}$

> The resolving power:

↳ $R = \frac{\lambda}{\Delta\lambda}$

↳ The Rayleigh criterion should be verified

LECTURE 7: DETECTORS

> Objects radiate, which we want to detect, and thus we need detectors, to create a visual representation of the observed scenery

> A detector uses the principle of converting an input signal into a representative electronic output signal

↳ Different principles: ① Photo-emission 0,1 – 5 μm
② Internal photo-electric effect 0.5 – 50 μm
③ Thermal 0.5 – 1000 μm

> Single element detectors generate an output signal proportional to the total power collected

↳ categories

> Image detectors have an active area physically divided

Detector Types

① Thermal
② Photon based
③ Semiconductor based focus

> The photo-electric effect is a phenomenon which occurs when high energetic light hits a material and electrons are ejected

↳ ① e^- are bound to valence band
② Added energy
③ e^- get excited and go to conduction band

↳ There is an energy difference E_{gap} depending on material

↳ The photon energy is more than E_{gap}

↳ $E_{ph} = \frac{hc}{\lambda} > E_{gap}$

> The detectivity is an indication of how well a detector can detect weak signals in presence of noise

> The lattice constant is a physical dimension defining the size and shape of the smallest repeating unit

↳ Typically the band gap depends on this, but not for MCT

> A photoconductor is the cheapest approach for photon detection

↳ Semiconductor is illuminated, and generates a current

↳ Consist of a thin layer of semiconductor material

↳ Conductance varies with photon flux

↳ The semiconductor absorbs light causing the conductivity to rise

↳ They are typically low performance due to the high noise levels

↳ $V_S = -\Delta i \cdot R$

↳ Read-out is done by use of processing and an ADC

> Photodiodes are more accurate

↳ They have:
1. + Higher speed
2. + Lower noise
3. + Better sensitivity
4. - Difficult fabrication
5. - Expensive

↳ Consist of 2 layers on top of each other, each doped with additional materials (n: extra e^-; p: extra holes)

↳ An electric field is generated between the n and p layers pulling e^- from the junction

↳ A PIN photodiode adds an intrinsic layer between the other 2 to increase efficiency

↳ An APD has an additional (4 total) layer, causing it to generate more than 1 e^-

↳ Read-out is similar as for photoconductors

> CCD detectors consist of an array of linked capacitors

↳ External circuit is required

↳ Each pixel has an absorbing semiconductor

↳ All accumulated e^- are converted to an output voltage

↳ Read-out consists of control logic, ...

↳ Binning combines charge of adjacent pixels during readout

> CMOS detectors are similar, but voltage conversion happens in each pixel

↳ They can access each pixel in random order

> Hybrid detectors integrate CCD and CMOS on the same Chip

Signal to Noise

> $S = I_s \cdot t \cdot QE$

> Noise : ① dark

↳ $n = \sqrt{I_{dark} \cdot t / q}$

② Shot

↳ $n = \sqrt{S} = \sqrt{m_{total} \cdot A \cdot \frac{\Delta\nu}{h\nu} \cdot F_\nu \cdot t \cdot QE}$

③ Thermal background

↳ $n = \sqrt{I_{back} \cdot t / q}$

④ Electronics

⑤ Conversion

↳ $n = \sqrt{kTC} / q$

↳ $N = \sqrt{\sum N_i^2}$

↳ $SNR = \frac{S}{N}$

LECTURE 8 : POLARIZATION

> The study of polarization relates to the evolution through time of the vector describing the EM field at one point in space

> We start with Maxwell's equations in vacuum:

↳ $\vec{\nabla} \cdot \vec{E} = 0$

↳ $\vec{\nabla} \times \vec{E} = \frac{\partial \vec{B}}{\partial t}$

↳ $\vec{\nabla} \cdot \vec{B} = 0$

↳ $\vec{\nabla} \times \vec{B} = \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t}$

↳ we can find for a light beam propagating in z-direction in free space, for the monochromatic case, the electric field is:

↳ $\vec{E} = E e^{i(\vec{k} \cdot \vec{r} - \omega t)} \vec{e}_0$ sinusoidal plane wave

↳ $\vec{E} = E_x \cos(kz - \omega t) \vec{x}_0 + E_y \cos(kz - \omega t + \Delta\phi) \vec{y}_0$ real part

> Optical components are sensitive to polarization, information on the atmosphere is found using it, and more

> The polarization state of the field is contained in the temporal variations of the amplitude vector

> There are 3 states:
① Elliptical   general
② Linear $E_x = 0$, $E_y = 0$, or $\Delta\phi = m\pi$
③ Circular $E_x = E_y$ and $\Delta\phi = (2m+1)\frac{\pi}{2}$
↳ >0: ccw, <0: cw

↳ Shapes are the map of the field on a plane over time

> There is a variation of scattered and absorbed light because biological material does not interact the same with left or right circular

> Light coming from the Sun/lamp is emitted by several independent emitters, thus there is no relation between E_x, E_y, and $\Delta\phi$, meaning the light can have every polarization state

↳ Every 10 ns, E_x, E_y, $\Delta\phi$ for one emitter change

↳ Unpolarized light has every polarization state without preference, and they change quickly

> The degree of polarization (0-1) indicates how much light is polarized

> Also a degree of linear polarization

> Polarization is quantified using the preferred direction α

> Polarization can be changed using a linear polarizer which blocks one direction of the vibration

> Common detectors measure the intensity, not the electric field

↳ $I = \varepsilon_0 c \langle E^2 \rangle_T$

↳ $I = A|E|^2$

Phase Retarders

> light has different propagation speeds depending on incident polarization

↳ There are 2 axes: ① Fast (small n)
② Slow (large n)

↳ phase retarders give $\vec{E}$ along the slow axis an extra $\Delta\phi$, changing the phase

↳ A retarder with a slow horizontal axis and a $\Delta\phi$ produces the same state as one with a fast vertical axis and $\Delta\phi$

↳ when $\Delta\phi = \pi$, the retarder is a half-wave plate

↳ linear: rotates with 2θ
↳ circular: ccw ↔ cw

↳ when $\Delta\phi = \frac{\pi}{2}$, the retarder is a quarter-wave plate

↳ linear: to circular if $\theta = \pm 45°$, else to elliptical
↳ circular: to linear

Measuring

> Polarimetry is the determination of the polarization state of a beam

↳ Different methods: ① Sequential measurements
② Division on detector
③ Spectral / Polarization modulation
④ ...

① ↳ Simplest method: using a linear polarizer on a rotating mount

↳ The detector has sequential acquisition at different orientations

↳ Can not solve $\Delta\phi$, and can't differentiate circular from natural

↳ A more advanced form is a fixed linear + rotating $\lambda/4$

↳ This can identify every state, and $E_x, E_y, \Delta\phi$ can be found with Fourier

② ↳ Camera with integrated pixelated polarizer

↳ Each pixel has different angles, thus a snapshot can be used to determine polarization state

↳ Some resolution is lost

↳ Can not differentiate circular vs unpolarized

Components

> Diffraction gratings in reflection are polarization sensitive

↳ Measurement and detection are necessary for measurements

Atmosphere

> The Sun yields unpolarized light

↳ The oscillation of electric dipoles is parallel to the vibration direction

↳ Re-radiation happens in a plane perpendicular to the vibration, and a reduced intensity in observation direction

↳ There is no emission in vibration direction

↳ Depending on observer position, some parts acquire a preferential orientation for the electric field → partial polarization

LECTURE 9: INTERFEROMETRY

> We know waves have a wavelength and a frequency — related

> Waves are subject to superposition: ① Constructive interference
② Destructive interference

↳ For interference: ① ≥2 waves
② Same frequency
③ Coherent — definite phase relation

> $E = E_1 + E_2$

↳ $I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\Delta\varphi$
↳ interference term

↳ If $I_1 = I_2 = I_0$:

↳ $I = 2I_0(1 + \cos\Delta\varphi) = 4I_0\cos^2\left(\frac{\Delta\varphi}{2}\right)$

> Detection of light is an integrating process — in space and time

↳ Time: A detector needs a certain amount of time to collect enough photons
↳ Space: A detector has a finite size

> The coherence of light is the degree to which waves in a beam maintain a consistent phase relationship

> Temporal coherence: How well φ is predictable over time

↳ High: fixed fluctuation in spacing of wavefronts
↳ Low: Random fluctuation in spacing of wavefronts

> Spatial coherence: How well φ is predictable in space

↳ High: fixed fluctuation in the shape of wavefronts
↳ Low: random fluctuation in the shape of wavefronts

> In an interferometer, the same source is split and recombined to interfere

↳ ① Wavefront division interferometers — e.g. double slit
② Amplitude division interferometers

① ↳ Young's Double Slit

↳ Path difference: $d\sin\theta = n\lambda$; $\theta \approx \frac{x}{L}$ — $n \in \mathbb{N}$ for bright, $n \in \mathbb{N} + \frac{1}{2}$ for dark

② ↳ Michelson Interferometer

↳ use of beam splitter and mirrors

Detection of Gravitational Waves

> Gravitational Waves are ripples in space-time

↳ Strength is characterized by strain amplitude

↳ $h_0 = \frac{\Delta L}{L}$

↳ Even for large L, ΔL is very small

↳ We use Michelson interferometer to measure with suspended test masses

↳ $E_{out} = -iE_{in} e^{i2kL} \sin(2k\Delta L)$

↳ $P_{out} = P_{in} \sin^2(2k\Delta L)$

↳ We measure $\Delta\varphi$ using the induced displacement

↳ $\Delta\varphi = \frac{4\pi}{\lambda} \Delta L$

↳ As we measure ΔL and h_0 is fixed, we increase L to get a larger ΔL (easier to measure)

↳ Done through adding additional mirrors

↳ $\Delta\varphi = \frac{4\pi}{\lambda} \Delta L = \frac{4\pi}{\lambda} h_0 L_{eff}$; $L_{eff} = \frac{2F}{\pi} L$

↳ The mirrors create a Fabry-Perot cavity, allowing the longer length

↳ Resonance occurs in the cavity when the light constructively interferes

↳ $FSR = \frac{\Delta\lambda}{\delta\lambda}$

↳ $F = \frac{\pi\sqrt{r_1 r_2}}{1 - r_1 r_2}$

↳ We have three parts of the beam:
1. Reflected
2. Transmitted
3. Circulating

↳ $E_{refl} = -r_i E_{in} + t_i r_e e^{i2kL} E_{circ}$

↳ $E_{trans} = t_e E_{circ}$

↳ $E_{circ} = t_i E_{in} + r_i r_e e^{i2kL} E_{circ}$

↳ Typically $r_i r_e$ is chosen to be around 1, making it such that there is resonance when $L = \lambda/2 \cdot n$

> GW interferometers suffer from noise

Interferometry in Space

① LISA is a GW interferometer in space
↳ Ground-based are sensitive in a small bandwidth only

> The induced $\Delta\varphi$ is related to the frequency
↳ $\varphi_{GW} = 2\pi f_{GW} t = 2\pi f_{GW} \frac{L}{c}$

↳ In space, we can have much larger L, and there is less noise

> Two types of scattering: ① Specular   smooth
② Diffuse   rough

↳ Stray light is caused by scattering, ghost beams, transmitted beams

↳ Coherent scatter occurs when stray and main have same $\Delta\varphi$
↳ Incoherent scatter when not

↳ Required surface smoothness:
↳ $\delta L = \sqrt{\frac{P_{ST}}{P_{MB}}}\, \delta x$

② Nulling interferometry for detection of exoplanets

↳ Requirements: ① High spatial resolution
② High contrast performance
③ High sensitivity

↳ Detection done with nulling interferometry

↳ 2 telescopes collect light of star and planet, with interferometer designed to destructively interfere the light of the star, and constructively the planet light

↳ High spatial resolution requires large baseline

White Light Interferometry

> For GW detection we use high coherence interferometry

↳ A high coherence source has high temporal and spatial coherence
↳ A low coherence source only has high spatial coherence

> White light interferometry is used for surface height measurements

↳ Normally a laser is used as input because of its narrow optical spectrum

↳ For WLI, a broadband source is used

↳ It is split into the arms, and a reference mirror can be moved as a function of the optical path difference

↳ $\Delta\varphi = \frac{2\pi}{\lambda}\Delta z = \frac{2\pi}{\lambda}(z_R - z_S)$

↳ The interfering beam is measured

↳ $I(z_{M_1}, z_{M_2}) = S_0\left(R_{M_1} + R_{M_2} + 2\sqrt{R_{M_1}R_{M_2}}\, e^{-(z_{M_1}-z_{M_2})^2\Delta k^2} \cdot \cos(2k_0(z_{M_1}-z_{M_2}))\right)$

↳ For monochromatic, the exponential is 1

↳ For broadband, the interference of all colors is combined

↳ An interferogram is a localized interference pattern around zero OPD for a broadband light source

↳ light coherence length: $\delta_z = \frac{2\ln(2)}{n\pi}\frac{\lambda_c^2}{\Delta\lambda}$

↳ This gives the OPD range over which interference occurs

> we can use this to see the reflectivity of different surfaces

> or to examine the different layers in the eye

LECTURE 10: OPTICAL COATINGS

> when light interacts with matter : ① Absorption
② Reflection / scattering
③ Transmission

> Waves :

↳ $\lambda = \frac{c}{f}$; $\lambda' = \frac{c}{nf}$

↳ $OT = nd$

↳ Refraction happens because velocity changes

↳ $n = \frac{c}{v} = \sqrt{\frac{\varepsilon\mu}{\varepsilon_0\mu_0}} = \sqrt{\varepsilon_r\mu_r}$

↳ Magnetic permittivity (μ_r)
↳ Electric permittivity (ε_r)

> Energy must be conserved

↳ $E = hf = \frac{hv}{\lambda}$ ⇒ f needs to change

> There is total internal reflection for :

↳ $\theta_c = \arcsin\left(\frac{n_1}{n_2}\right)$

Electromagnetic Wave Boundary Conditions

> To determine field magnitudes we need the BCs at the interface

↳ For charge accumulation $\vec{E}_1 \neq \vec{E}_2$

↳ $\varepsilon_1 E_{1\perp} = \varepsilon_2 E_{2\perp}$

↳ $E_{1//} = E_{2//}$

↳ For normal incidence :

↳ $\frac{E_R}{E_I} = \frac{n_1 - n_2}{n_1 + n_2}$

↳ If $n_1 < n_2$, there is a phase flip

↳ For a thin film, we generally have a phase flip ($n_{film} > n_{air}$) at the top surface but not at the bottom,

↳ For very thin films, the two reflections will destructively interfere

↳ $E_{tot} = E_I R\left(-1 + T^2 \cos\frac{4\pi d}{\lambda}\right)$

> At the polarization angle, p-polarized light will not be reflected if :

↳ $\theta_B = \arctan\frac{n_2}{n_1}$

↳ At this angle there is pure s-polarized reflection

Thin Film Coatings

> Can create: ① anti/high reflection
② wavelength selective

↳ Materials define refractive indices and interference (reflection

> Coatings are used to enhance: ① Reflection
② Transmission
③ Absorption
④ Polarization

↳ Constructed by: ① Thin layers of dielectrics
② Thick layer of metal
③ Combinations

① ↳ Utilize interference

② ↳ First surface mirrors cause pure reflection
↳ Second surface mirrors have a ghost reflection as the light is first passed through a substrate

↳ A second surface can protect the coating

Single and Multi-Layer Optical Coatings

> Anti-reflective coatings use destructive interference in a film

↳ $\Delta\varphi = 2tn_c$

> Intensity of a reflected beam

↳ $I = \left(\frac{1-p}{1+p}\right)^2 \cdot I_0$; $p = \frac{n_1}{n_2}$

↳ For equal intensity, $\frac{n_1}{n_2} = \frac{n_2}{n_3}$

↳ Simplest: $n_{film} = \sqrt{n_{substrate}}$

> OPD is a function of the angle (higher for higher), causing a phase difference per angle

↳ Complete cancellation can be achieved with ≥2 layers

↳ Two-layer AR coatings are the simplest form of V-coatings

↳ On JWST, λ>400 nm has nearly no reflection due to 2LARC

> A quarter wave stack is a dielectric multilayer system for high reflective coatings

↳ Has alternating layers of high and low index layers with OPD = $\frac{1}{4}\lambda$

↳ Highly reflecting for λ_{des}

↳ Based on constructive interference

↳ $R = \left[\left(1 - \left(\frac{n_H}{n_L}\right)^{2p} \frac{n_H^2}{n_s}\right) / \left(1 + \left(\frac{n_H}{n_L}\right)^{2p} \frac{n_H}{n_s}\right) \right]^2$

> Bandpass filters transmit a range of λ and block the rest
> Short pass edge filters transmit all shorter λ
> Long pass edge filters transmit all larger λ

} at 0°

> Dichoric filters reflect specific λ and transmit others — at 45°

Temperature and Space Environment Impact

> A thin film has a different n for a different T, also thus changing the reflectance

↳ They also have thermal expansion

> In space, there is:
① Radiation
② Temperature extremes
③ Atomic oxygen
④ Vacuum
⑤ Contamination

↳ These all lead to degradation

LECTURE 11: RADIOWAVES AND SUB-MM INSTRUMENTS

> Radar, sonar, lidar all use wave reflections to detect objects
  ↳ Radio ↳ Sound ↳ Light

↳ Radar is an active instrument

↳ A single antenna is used for transmission and reception

↳ A single pulse is transmitted, reflected, and the propagation time measured

↳ Reflectivity and scattering affect the reflection

↳ Range $= \frac{ct_R}{2}$

> For a uniformly radiating antenna transmitting over a sphere

↳ Power density $= \frac{P_t}{4\pi R^2}$

> For a directive antenna:

↳ Emitted $= \frac{P_t G_t}{4\pi R^2}$; $G = 4\pi \frac{A_{eff}}{\lambda^2}$; $A_{eff} = AK$

↳ Received $= \frac{P_t G_t}{4\pi R^2} A_r = \frac{P_t G_t}{4\pi R^2} \frac{G_r \lambda^2}{4\pi} = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2}$

> For the monostatic case, the transmitter is the receiver

↳ The target only intercepts and reflects a portion of the emission corresponding to its cross-sectional area

↳ Reflected $= \frac{P_t G_t}{4\pi R^2} \sigma$

↳ Also, it is not considered a flat mirror

↳ Reflected P.D. $= \frac{P_t G_t}{(4\pi R^2)^2} \sigma$

↳ Received $= \frac{P_t G_t^2 \lambda^2 \sigma}{(4\pi)^3 R^4}$

> For the bistatic case, the transmitter is not the receiver

↳ $P_r = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R_t^2 R_r^2}$

> Pulsed radar sends high f pulses with width τ

↳ Range resolution $S = \frac{c\tau}{2} = \frac{c}{2BW}$

↳ Is the ability to distinguish 2 or more sources in the same bearing but at different ranges

> A continuous wave can be frequency modulated f sweep

↳ Detector receives an echo

↳ $S = \frac{c\Delta t}{2} = \frac{c\Delta f \frac{dt}{df}}{2} = c\Delta f / 2\frac{df}{dt}$

> Radio wave detectors can measure both amplitude and phase of the EM fields (VIS-IR only 1)

> We can observe binary asteroids using delay-Doppler techniques

↳ $B = \frac{4\pi D}{\lambda P} \cos \gamma$

> With several layers, there will be an echo delay between the signals

↳ $P_{ss} = P_t \left(\frac{G\lambda}{8\pi(H+z)} \right)^2 T_s^2 R_{ss} e^{-2\pi f \tan \delta \tau}$

↳ We can see different reflections from layer composition

> LiDAR can be used for surface topology

LECTURE 12: LASER BASED INSTRUMENTS (1)

> Why: ① Dependency on others
> ② Need for connection

↳ Currently, wireless is done mainly through RF as it is robust and mature

↳ RF suffers from divergence

↳ $\theta_{div} = \frac{2.44}{D} \lambda$

↳ This causes power loss, interference, ...

↳ As laser has a lower λ, θ_{div} is lower

Challenges

① Pointing (low θ_{div})
② Clouds occlusion and fog
③ Atmospheric attenuation
④ Atmospheric turbulence
⑤ Sun blinding

> $\theta_{div} = \frac{\lambda}{\pi w_0}$

↳ $D_{spot} = 2 \cdot \theta_{div} \cdot L$

> Other issues: ① Background radiation
> ② Wavefront errors
> ③ Laser safety

System Choices and Applications

> The OSI model consists of several layers for proper communication

↳ The physical layer consists of: ① Transmitter

↳ Data source, encoder, laser, modulator, booster EDFA

② Medium

↳ 2 optical systems, free space

③ Receiver

↳ Pre-amp EDFA, demodulator, decoder

> We use the O, S, C, L, and E bands for communications

↳ Most work is done at 1550 nm (C-band) as it is the optimum (minimal loss)

> Operational phases: ① Acquisition
② Tracking
③ Communication

Performance

> Key performance goals: ① High throughput
② Quasi error free
③ High availability
④ Low latency

↳ with: ① Low cost
② Low bandwidth
③ safe
④ small
⑤ Low complexity

> A link budget shows how much power can be lost in the link

↳ $P_R = P_T \cdot G_i \; L_i$

↳ $P_{RX} = \underbrace{P_{TX} + G_{TX} - L_{TX}}_{\text{Transmitter}} - \underbrace{L_M}_{\text{Medium}} + \underbrace{G_{RX} - L_{RX}}_{\text{Receiver}}$ [dB]

> Free space loss $L_{FS} = \left(\frac{\lambda}{4\pi L}\right)^2$

> $G_{TX} = \frac{8}{\theta_{div}^2} = 2\left(\frac{2\pi w_0}{\lambda}\right)^2$

> $G_{RX} = \left(\frac{\pi D_R}{\lambda}\right)^2$

> The channel capacity is the maximum achievable datarate

↳ $C = B \log_2 \left(1 + \frac{S}{N}\right)$

Gaussian Beams

> Gaussian beams are propagation invariant

↳ $I(r,z) = \underbrace{I_0}_{\text{source}} \underbrace{\left(\frac{w_0}{w(z)}\right)^2}_{\text{axial}} \underbrace{e^{-(2r^2/w(z)^2)}}_{\text{radial}}$

↳ The width propagates over a distance

↳ $w(z) = w_0 \cdot \sqrt{1 + (z/z_R)^2}$; $z_R = \pi w_0^2 n / \lambda$ → Rayleigh range

↳ $\theta_{div} = \frac{\lambda}{\pi n w_0}$

Pointing Errors

① Static
② Dynamic pointing jitter

↳ Results in loss of power and scintillation

① > $T_{p,e} = e^{-2\theta_{p,e}^2 / \theta_{div}^2}$; $\theta_{p,e} = \frac{r}{L}$

> There is a trade-off between pointing error and divergence

② > $T_{p,a} = \frac{\theta_{div}^2}{\theta_{div}^2 + 4\sigma_{pj}^2}$

> $T_{p,s} = P_0^{4\sigma_{pj}^2 / \theta_{div}^2}$

LECTURE 13: LASER BASED INSTRUMENTS (2)

Pointing Systems Architecture

> A passive system consists of a telescope, mirrors, beam splitter, transmitter, and receiver

↳ Various pointing systems can be added: ① Body pointing
② Coarse pointing assembly
③ Fine steering method
④ Point ahead mirror

② ↳ Requirements: ① Large range
② Medium-high resolution
③ 2 axis steering
④ Low transmission losses

↳ Types: ① Periscope

↳ 2 mirrors
↳ Rotation perpendicular to optical axis

② Prism based

↳ light propagates through prisms
↳ No cable wraps required

③ Gimbal

↳ Rotate the entire terminal
↳ No movement in optical system

③ ↳ Requirements: ① Small range
② High bandwidth
③ Low residual error
④ 2 axis tilt

↳ For precise control of motion

↳ Consists of: ① Mirror
② Sensors
③ Actuators
④ Hinge
⑤ RTC

④ ↳ There is a loss due to movement of the satellites in the link

↳ A PAM points the mirror at the angle between tx and rx beam

> The tracking detector either uses an image or a quad cell

> A control loop is present for the tracking controller
↳ Typically PID

Turbulence

> Turbulence causes a fluctuation of n in the light path
↳ Driven by T differences → wind shear and buoyancy
↳ Causes image distortion and blur

> Regions: ① Energy injection
② Energy transfer
③ Dissipation

> Atmospheric turbulence causes: ① Beam wander
② Beam spread
③ Scintillation
④ AoA fluctuations
⑤ Spot widening

① ↳ $\sigma_{BW}^2 = 0.54 \left(\frac{\lambda}{D}\right)^2 \left(\frac{D}{r_0}\right)^{5/3}$
↳ Similar to jitter

②③ ↳ Wider beam with equal energy
↳ $S_{BS} = \left(1 + \left(\frac{D_c}{r_0}\right)^{5/3}\right)^{-6/5}$
↳ $L_{sc} = \left(3.3 - 5.77\sqrt{-\ln p_{out}}\right)\sigma_I^{4/5}$

④ ↳ $\sigma_\alpha^2 = 0.18 \left(\frac{D}{r_0}\right)^{5/3} \left(\frac{\lambda}{D}\right)^2$

ADD-ON FROM EXERCISES

> Bit Error Rate is the ratio of wrong over total bits
  - Function of normalized bit energy E_b and variance of noise σ^2
    - $E_b = \left(\frac{V_1 - V_0}{2}\right)^2$
  - $BER = \frac{1}{2} \operatorname{erfc}\left(\sqrt{E_b / 2\sigma^2}\right)$
  - $SNR = E_b / \sigma^2$

LECTURE 14: HIGH ENERGY IMAGERS

> X-rays and γ-rays are very high energy, and thus have high penetration power

↳ Classification: ① Soft X
② Classical X
③ Hard X
④ γ

> X-rays are emitted by: ① Thermal (BB, bremsstralung)
② Nonthermal (collisions, scattering, synchrotron)

① ↳ Black body emission emits in X-ray for very high T
↳ Thermal bremsstrahlung occurs in high T environments, produced by fast moving free e^- being deflected by a proton

② ↳ Collisional bremsstrahlung has an e^- colliding with an atom, emitting a bound e^-
↳ Characteristic X-rays happen when an inner e^- is ejected and replaced by a higher energy e^-
↳ Inverse compton is when a low energy photon collides with a relativistic e^-, emitting energy at the expense of the e^-
↳ Synchrotron emission happens when a relativistic particle spiralizes in an electric field

> Energy spectra: ① Power law
② Black body
③ Thermal bremsstrahlung

> γ-rays are created in: ① Radioactive decay
② Nuclear fission
③ High energy collisions, secondary

> Pretty much all stars emit X-rays

Detection

> Challenges: ① Penetrating power
② Background noise
③ General space mission problems

> A soller collimator uses angular filtering, limiting divergence

> If a ray glances the surface, it will reflect, and not penetrate, happening for the grazing incidence

↳ A Wolter telescope uses this to focus the rays at one point

> Diffraction gratings can also be used

> Detectors : ① Proportional counters -0.5
② Microchannel plates -1
③ Semiconductors -1
④ CCD -0.5
⑤ Micro - calorimeters 1

> The resolving power depends on the type used ⟶ I

LECTURE 15: INSTRUMENTS FOR CHARGED PARTICLES

> We have sub-nuclear particles and nuclear particles

> We can measure: ① Charge
② momentum
③ Track
④ Type
⑤ Flux
⑥ Dose
⑦ Dose rate
(① – ④: for charged particles)

> In space, we have radiation due to: ① trapped particles
② Solar energetic particles
③ Cosmic rays

> To detect particles in space, they need to reach the monitor, and interact with it

> A detector has 3 parts: ① Absorber
② Observable phenomenon from the interaction
③ Measuring method

> When interacting with the e^-, the particle loses energy and the atoms become excited or ionized
> when interacting with the nucleus, the particle is deflected causing scattering

> Cherenkov radiation happens when $v_p > c$ in the medium

> At a boundary crossing, an X-ray photon may be created (transition radiation)

> The energy loss $-\left(\frac{dE}{dx}\right)_{coll}$ is described by the Bethe-Bloch formula
↳ This has 4 zones: Ⓐ Fast decrease
Ⓑ Minimum energy loss
Ⓒ Slow relativistic increase
Ⓓ Constant loss per unit length

> Energy loss depends on material and particle mass

> Detector types: ① Ionization
② Scintillation
③ Solid state