# Astro 331X: Payloads 

## EM Spectrum

| | Gamma Rays | X-rays | UV | visible | infrared | Microwave | Radio |
|---|---|---|---|---|---|---|---|
| Wavelength | $10^{-4} \to 0.1$ nm | $0.1 \to 10$ nm | 10nm → 380nm | 380 → 770nm | 770nm → 1mm | 1mm → 30cm | 30cm + |
| Payload | | | | Vis. Camera* | IR Camera* | Radar/SAR* | Communications*, GPS |

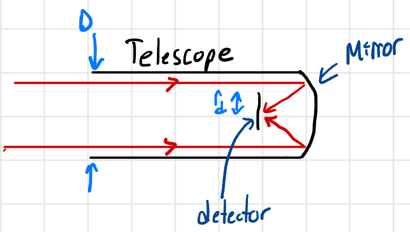
Laser Communications
Lidar

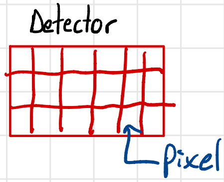
- Wavelength ranges may vary depending on the reference used.
- These are from "Intro to Optics" text by Pedrotti

- GPS: ~1575 MHz

* We will discuss these payloads in more detail for this class

## Visible Cameras




- Telescope focuses incoming light (photons) onto a detector
- Detector, e.g. CCD, converts photons to electrons, charge builds up on each pixel over exposure time
- After exposure, charge of each pixel is recorded → image
- Passive Sensor: relies on reflected EM radiation from another source (e.g. sun)

## Figures of Merit

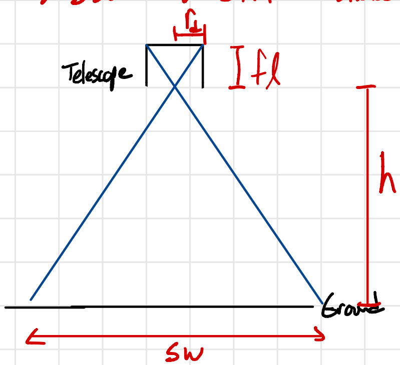
1) Spatial Resolution: dimension of smallest identifiable object

$$\text{Res} = \frac{2.44\,\lambda\,h}{D}$$

wavelength ($\lambda$), distance to object ($h$), Telescope aperture diameter ($D$)

- fxn of telescope, distance and wavelength being sensed.
- Lower Res. is good
- Better w/ smaller h, smaller λ or larger D

## 2) Swath Width: Distance across image on the ground




$$SW = \frac{2 r_d h}{fl}$$

← detector radius

← distance to target

↑ focal length

- typically a higher SW is good b/c you can see more.
- SW and Res are competing requirements
  → $h \uparrow \Rightarrow$ SW better, Res worse

### Mission Applications

- "Normal" imagery, e.g., google maps!

### Satellite Design Considerations

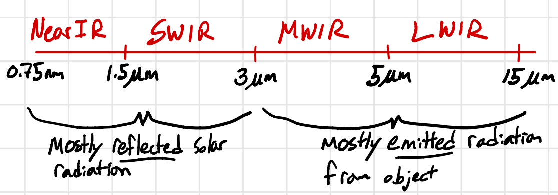
- Orbit/altitude must be chosen to balance Res. and SW requirements
- Rocket size and performance can be limiting factors
  → Optics are heavy!
  → Large telescopes yield good performance, but must fit in rocket fairing and be light enough to reach orbit.

## IR Cameras

- Same basic design/operation as visible cameras
- Passive sensors
- Same resolution and SW eq'ns

- Note: IR wavelengths are larger than vis ⇒ IR res. will be worse

### IR Spectrum




Near IR: reflected light, not heat

Shortwave IR: can travel thru smoke, clouds, etc.

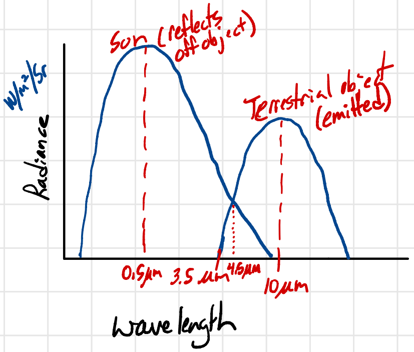
Midwave IR: high heat, rockets, fires, etc.

Longwave IR: less heat, people, ground, etc.

- objects on Earth do emit a little in SWIR, but much more energy is reflected at those wavelengths

For terrestrial objects (300K) emitted radiation surpasses reflected solar radiation in MWIR

## Black Body Curves




← plot shows blackbody curves for sun (T=5800K) and an object @ 300K

(Fig 7.1 in Olsen)

- So, for SWIR, Tgt must be illuminated,
- Not so for MWIR or LWIR sensing

## Mission Applications

### 1) Thermal Imaging

- View target by the radiation it emits
- Estimate temperature using Stephan-Boltzmann Law

$$S = \varepsilon \sigma T^4$$

Estimated emissivity (0→1)

Total power emitted (area under black body curve)

Constant $5.669 \times 10^{-8} \frac{W}{m^2 K^4}$

object temperature

- The sensor can collect total power, or power over several $\lambda$ bands, but doesn't necessarily know $\varepsilon$ of objects $\varepsilon$ must be estimated.

Notes:
- Emitted radiation can be determined by the CCD charge reading: More power ⇒ more photons → higher charge
- Collecting energy over a few $\lambda$ bands allows estimation of the Black-body curve ⇒ estimate of temp.
  → $\varepsilon$ just moves curve up/down but does not change slope

### 2) Weather

- Surface temps
- Cloud composition
- Vegetation + soil moisture → 2 ways:
  1) Dry soil heats up more quickly + is hotter
  Can calibrate sensor w/ known soil moisture readings
  2) Water absorbs certain IR, $\lambda$. ∴ by looking @ reflected light in certain $\lambda$, can estimate water content.

### 3) Missile Warning → Good temporal resolution required

## Design Considerations

- Materials: Windows/lenses must be transparent to IR
  Detectors must absorb IR
  - different materials needed vs. visible
- Cooling: required for 2 reasons
  1) Reduce unwanted emissions (warm objects emit IR light)
     - ensure camera does not record emissions from optical components
  2) Reduce noise in detector/improve sensitivity
     - Thermal vibrations in detector material releases electrons ("dark current")
     - Adds noise that could mask desired signal.

## Radar/Synthetic Aperture Radar (SAR)

### Radar Basics

Active Sensor: Microwave EM radiation is transmitted, hits a target and returns

Microwave radiation is produced by a magnetron.

Challenge

$$Res = \frac{2.44 \lambda h}{D}$$

$\lambda$: microwave $10^{-3}$
optical $10^{-7}$

- One of the challenges w/ Radar is related to res
  $\Rightarrow$ microwave resolution much larger!

relatively large $\lambda \Rightarrow$ poor resolution
$\rightarrow$ need large aperture (D)
- real or synthetic

$\rightarrow$ need different principle for image generation

## Figures of Merit

Radar range: $R = \sqrt[4]{\dfrac{P_t G^2 \lambda^2 \sigma}{P_R (4\pi)^3}}$

$P_t$: transmit power (W)
$P_R$: received power (W)
$\lambda$: wave length (m)
$\sigma$: radar cross section ($m^2$)
$G$: receiver/transmitter Gain

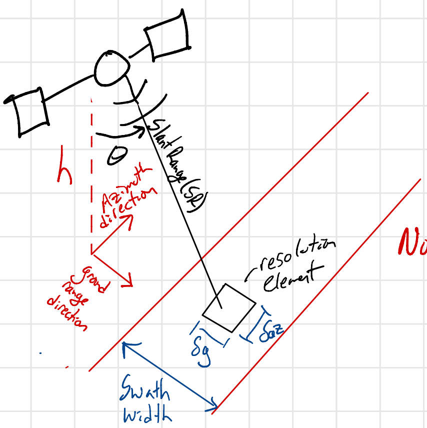
- use to calc. range to target given $P_R$, or calc. max possible range given min detectable $P_R$

RCS: Area which, if radiating the incident power isotropically, would produce the same received power in the Radar. Depends on Target size, shape, orientation, material and Radar wavelength

← will discuss gain later with comm

## Resolutions:

- for radar, we define 2 types of spatial resolution. Along the radar line of sight, and along the direction of motion.




Note: $SR = \dfrac{h}{\cos\theta}$

$\theta$: look angle

Radar "pulse width" $\tau$ (sec)

This is the length of time the radar transmits EM radiation before stopping to listen.

Slant range resolution: along radar Line of sight

$$\delta_{SR} = \frac{c\tau}{2}$$

- we care more about ground range res. which accounts for look angle $\theta$

Ground range resolution: $\perp$ to ground track

$$\delta g = \frac{c\tau}{2\sin\theta}$$

Both independent of range.

Notes:
- Both $\delta_{SR}$ and $\delta g$ are indep. of range + $\lambda$
- Ground range res actually improves as range ↑ since $\theta$, $\sin\theta$ ↑

- these eqns imply you want $\tau$ as small as possible. True, but then you have less power on target ⇒ less chance of detection.

## Azimuth Resolution: // to ground track

Real Radar (single pulse):

$$S_{az} = \frac{h\lambda}{\cos\theta \, D_{az}}$$

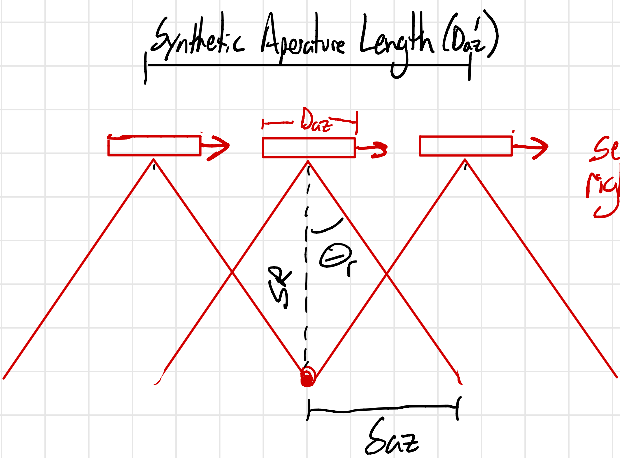
$D_{az}$: Diameter of antenna in direction of travel

Ex: $h = 300\text{ km}$
$\lambda = 0.015\text{ m}$ $\Rightarrow S_{az} = 1732\text{ m}$ :(
$D_{az} = 3\text{ m}$
$\theta = 30^\circ$

Dependant on range (h)! $\Rightarrow$ Poor Resolution.

Solution: Synthetic Aperture Radar

→ radar returns are combined while target is in view, forming a large Synthetic Aperture




Sensor moving to right, Target stationary

-Note: res is now only a fxn of antenna size, and smaller is better! Why?
-Smaller antenna, larger beam, $D'_{az}$ can be larger

$$D'_{az} = 2S_{az} = 2\left(SR\frac{\lambda}{D_{az}}\right)$$

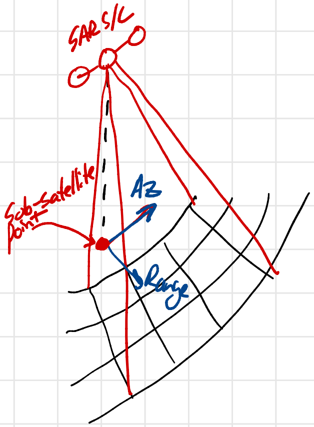
$$S_{az_{SAR}} = SR\frac{\lambda}{D'_{az}} = \frac{\cancel{SR}\cancel{\lambda}}{2\cancel{SR}\frac{\cancel{\lambda}}{D_{az}}} \Rightarrow \boxed{S_{az_{SAR}} = \frac{D_{az}}{2}}$$

SAR Az. Res. is only a fxn of antenna size! Smaller $D_{az}$ is better. Why? Smaller antenna → wider beam → $D'_{az}$ is larger

## SAR Image Generation: Basic Ideas

- here we'll just try to describe the basic ideas used to generate images. Reality it's quite a bit more complicated

To generate an image the system must map each return to a location in both range + azimuth directions




Range: Determined by time from pulse transmission to return receive

Azimuth: Determined by doppler shift in return.
→ returns from targets "in front" have higher freq (pos. doppler shift)
→ returns from targets "behind" have lower freq (neg. doppler shift)

- Target location in Range/Az can be determined for each pulse
- Multiple pulse returns can be combined + Range/Az map shifted based on doppler history to generate an image.

## Mission Applications

- All weather, day/night imaging

## Design Considerations

- Active System → higher power requirements compared to optical/IR
- Lots of processing required for SAR image generation

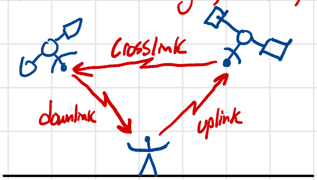
## RF Communications

Transmit and/or receive data:

Satellite data: telemetry (temp, voltage, position, etc)

Mission data: images, text, notifications, etc.

- we'll focus on comm systems using RF (longer wavelengths), but comm using lasers is also possible, and is becoming more common.

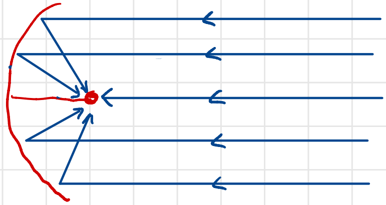



Uses an Antenna: Any device that converts electronic electronic signals to EM waves or vice versa

$\underbrace{\text{electronic signals to EM waves}}_{\text{Transmit antenna}}$ $\underbrace{\text{or vice versa}}_{\text{Receive Antenna}}$

- electronic signals are, e.g. signals in wires or cables.

Antenna Gain: Dish collects more energy and focuses



Paraboliz Antenna Max Gain:

$$G = \frac{4\pi A}{\lambda^2}\varepsilon$$

A: cross-section of dish

$A = \pi r^2$

$\varepsilon$: efficiency ($\%$: $20\% \Rightarrow \varepsilon = 0.2$)

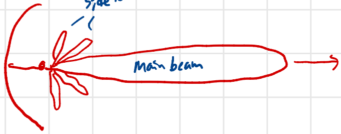
$\lambda$ in eq'n $\Rightarrow$ gain depends on signal!

$\varepsilon$: fxn of materials and/or manufacturing

- Gain changes based on direction

Antenna Beam Pattern:

- We saw that SNR drops w/ R. If the antenna has a gain >1, then it does not transmit or receive energy in all directions equally



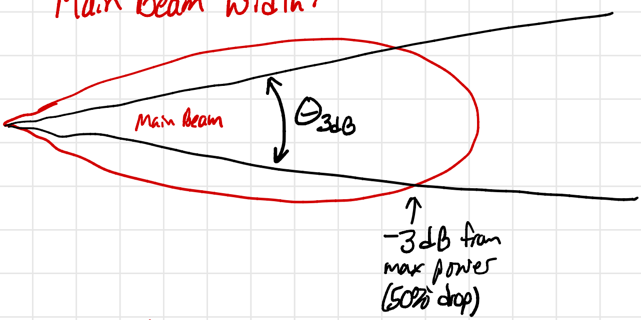

For best performance, want

Transmit antenna oriented so that receiver is in main beam

Receive antenna oriented so that transmitter of interest is in main beam

- Typically when we are designing an antenna, or planning how to use it, we care about the main beam. We'll generally point our antenna so that the target is in the main beam b/c it's easiest to collect that way.

## Main Beam width:




**General:** $\theta_{3dB} = \beta \dfrac{\lambda}{D}$ (radians)

$\lambda$: wavelength (m)
$D$: Antenna dimension in same plane as beam pattern (m)
$\beta$: Beamwidth fudge factor (unitless)
typically $0.5 \rightarrow 2.0$

**Figure of Merit:** Signal to Noise ratio (SNR)
Typically want $> 1$

$$SNR = \frac{P_t G_t \left(\frac{\lambda}{4\pi S}\right)^2 G_r}{k T_R B} = \frac{\text{Signal Power}}{\text{Noise Power}}$$

$P_t$: Transmit power
$G_t$: Transmit gain
$\lambda$: wavelength
$S$: range
$G_r$: receiver gain
$k = 1.38 \times 10^{-23}$ J/K
$T_R$: receiver temp.
$B$: receiver bandwidth

If listening, can control: $G_R$, $T_R$, $S$

← what can be controlled if transmitting?

- discuss min/max range

$R_{max} = \sqrt{(R_\oplus + h)^2 - R_\oplus^2}$