CLEMSON UNIVERSITY INTERNATIONAL CENTER FOR AUTOMOTIVE RESEARCH

# AuE 8930: Machine Perception and Intelligence

## Lecture: Signal, spectrum, and vehicle sensors


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# Outline

- Introduction
- Signal and Sensor Perception
- 1D Signal and A/D
- 1D Signal Time-domain Analysis
- 1D Signal Frequency Analysis
- 1D Signal Noise Analysis
- 1D Signal Processing and Filter Design
- Electromagnetic Spectrum
- Vehicle Sensors (Perception)

# 1D Signal: Wave

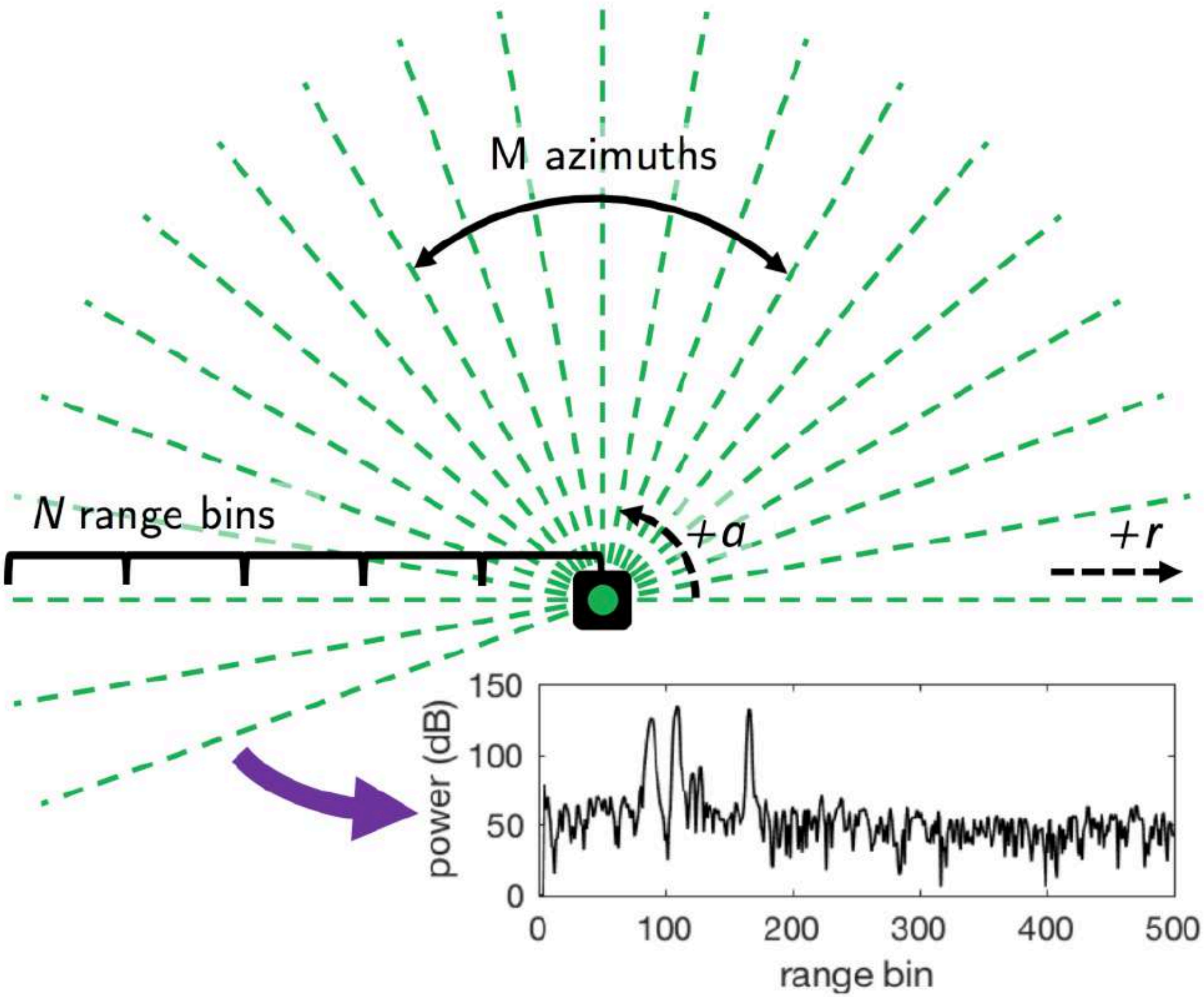
Time domain

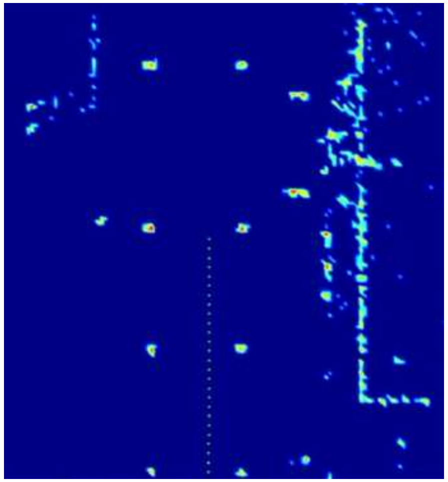
Frequency domain

Noise filter

Patterns

…



# 2D Signal: Image

Time domain

Frequency domain

Noise filter

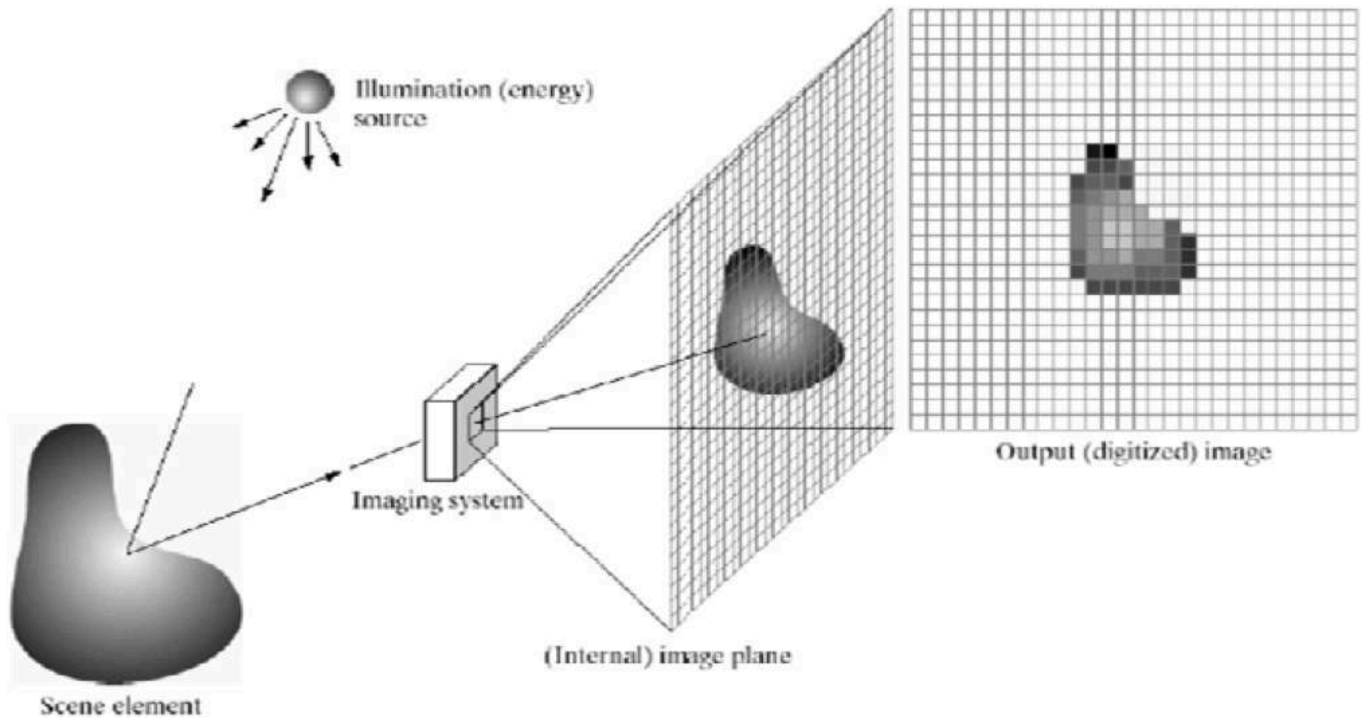
Multi-view

Features

Patterns

Understanding

…



# 3D Signal: Point Cloud

Time domain

Frequency domain

Noise filter

Geometry analysis, mapping

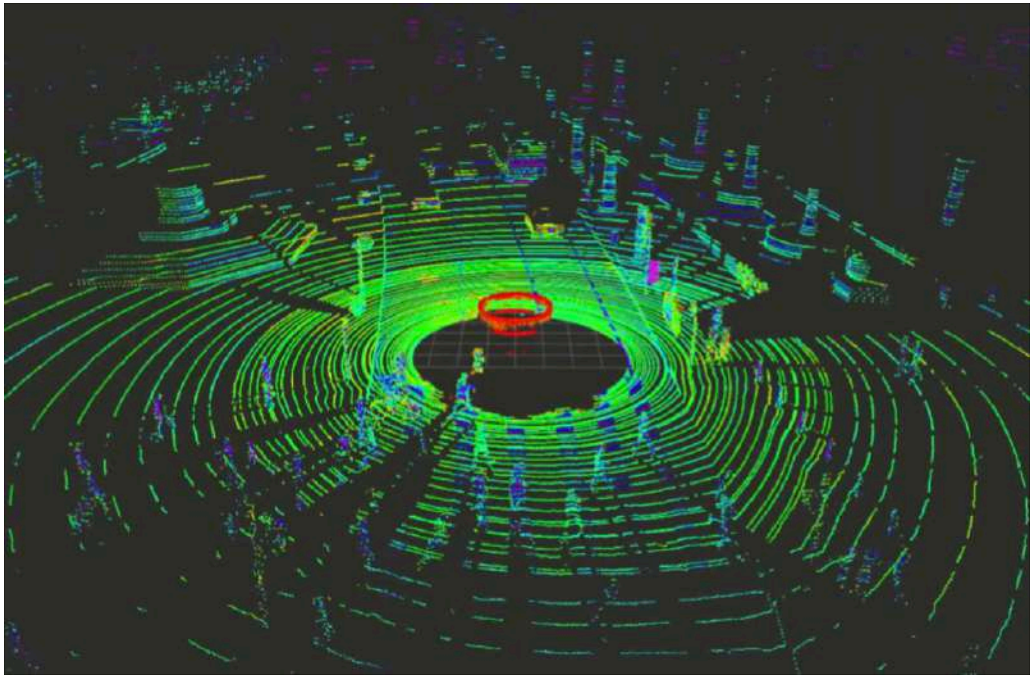
Features

Patterns

Understanding

…

Fuse with 2D vision

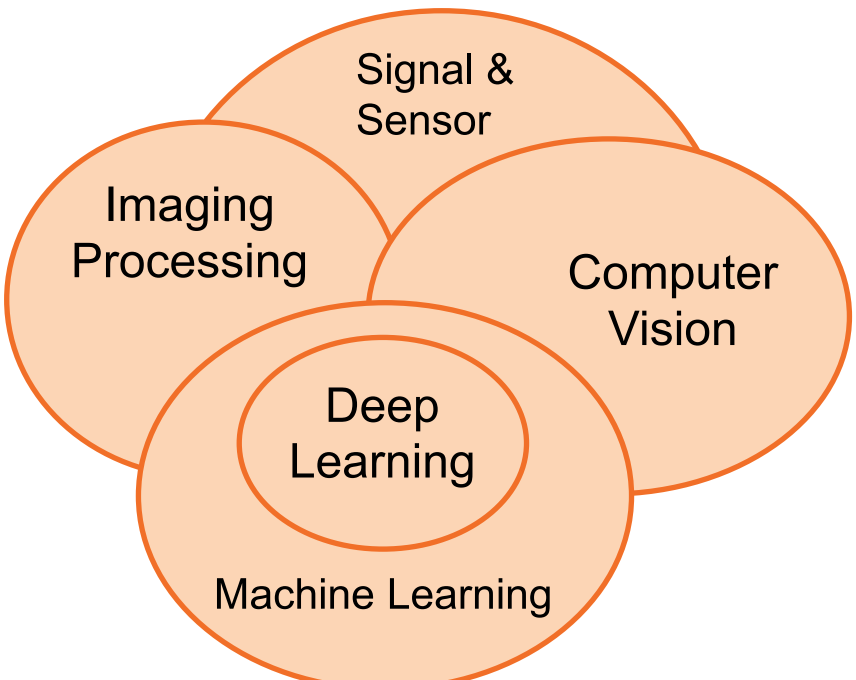


# Signal and Sensor Data Analysis

- Applications

  Vehicle perception
  ADAS (Advanced driver-assistance systems)
  Autonomy

- Areas




| | |
|---|---|
| Space | -Space photograph enhancement<br>-Data compression<br>-Intelligent sensory analysis by remote space probes |
| Medical | -Diagnostic imaging (CT, MRI, ultrasound, and others)<br>-Electrocardiogram analysis<br>-Medical image storage/retrieval |
| Commercial | -Image and sound compression for multimedia presentation<br>-Movie special effects<br>-Video conference calling |
| Telephone | -Voice and data compression<br>-Echo reduction<br>-Signal multiplexing<br>-Filtering |
| Military | -Radar<br>-Sonar<br>-Ordnance guidance<br>-Secure communication |
| Industrial | -Oil and mineral prospecting<br>-Process monitoring & control<br>-Nondestructive testing<br>-CAD and design tools |
| Scientific | -Earthquake recording & analysis<br>-Data acquisition<br>-Spectral analysis<br>-Simulation and modeling |

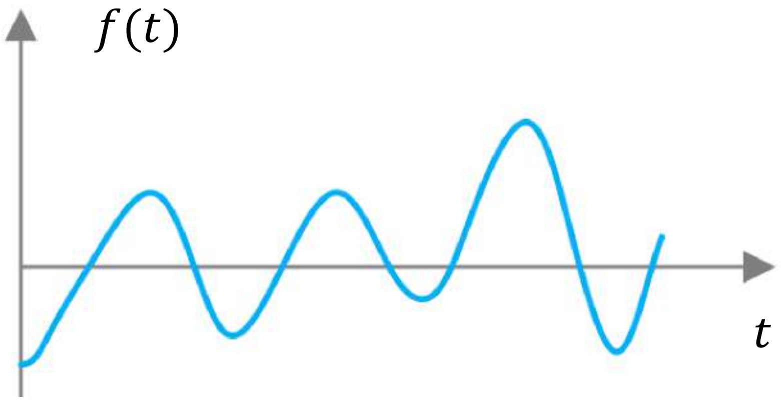
# Signal and Sensor Perception

- Perception for physical quantities
  Transduction principle - conversion of energy from one form to another

- Proprioception:
  Position, speed, acceleration, torque, battery level …

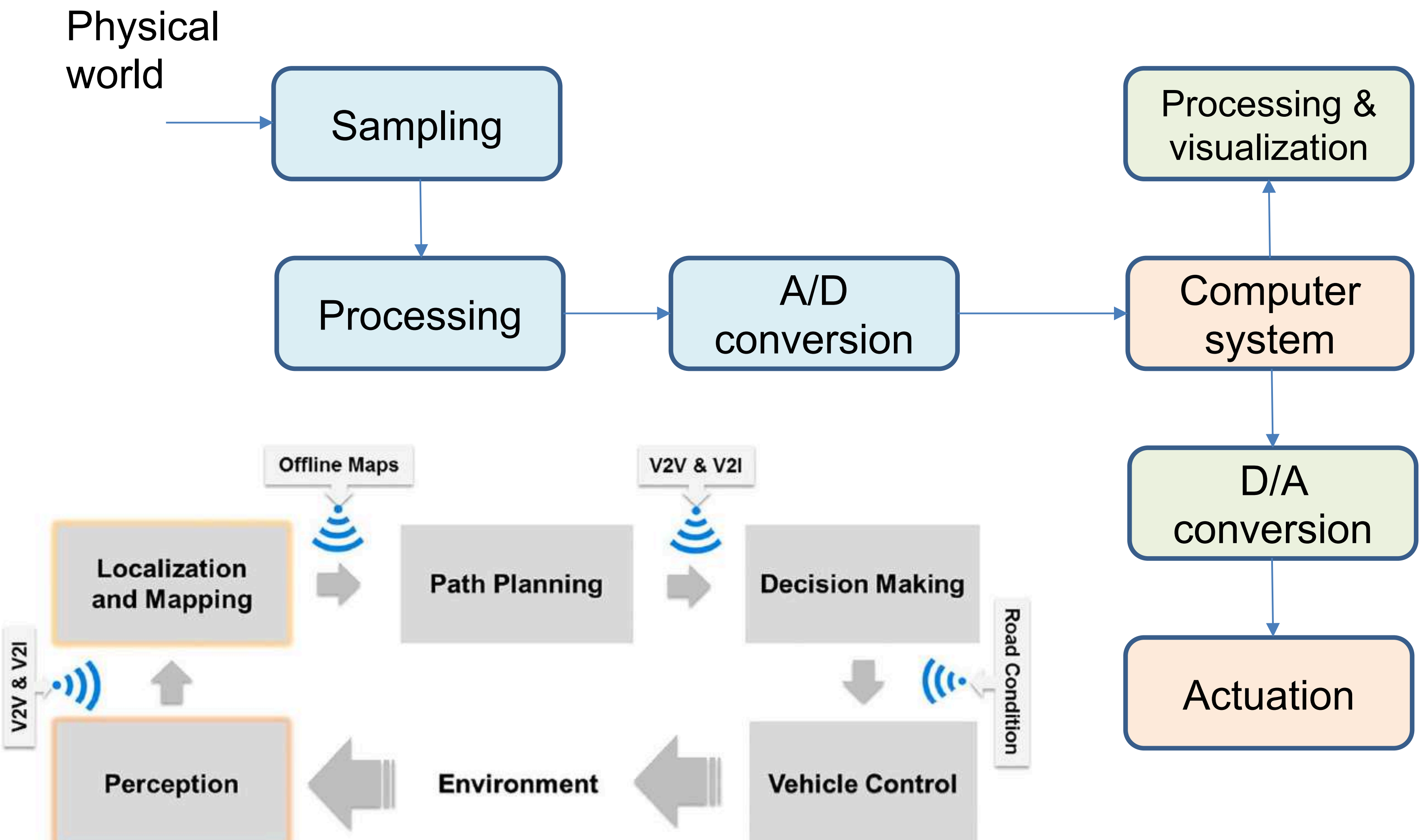
- Exteroceptive:
  Scene, geometry, object, …

- Analog signal
  Continuity in
  - Time domain
  - Amplitude



# Signal and Sensor Perception

- Sensor perception → vehicle actuator control

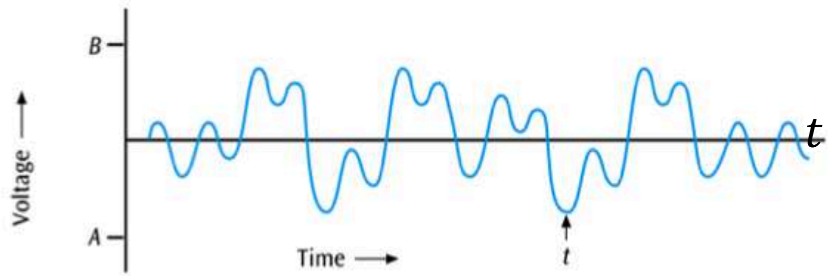


# Signal and Sensor Perception

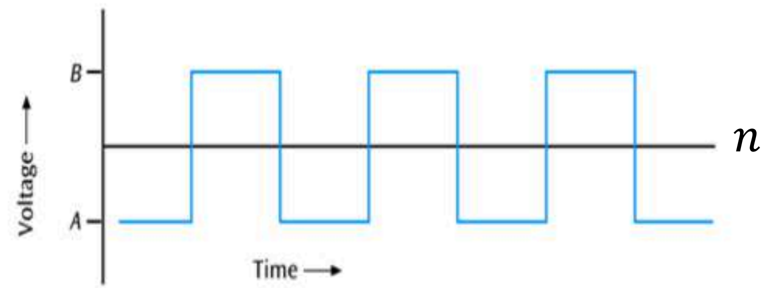
- Analog signal VS. Digital signal

A/D (Analog-to-Digital)

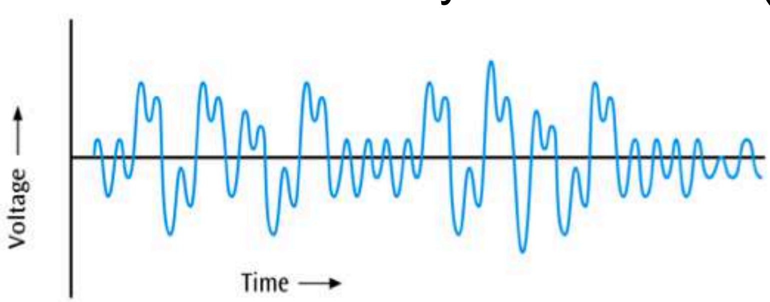
$f(t)$

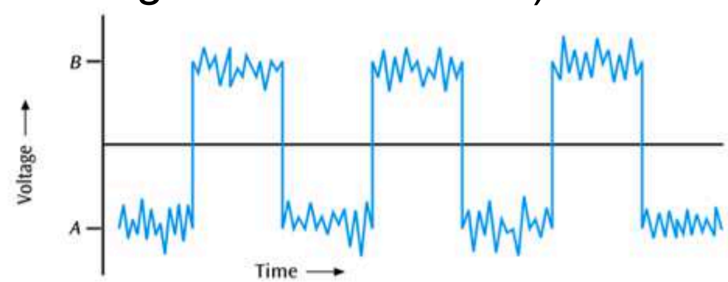



$f(n)$



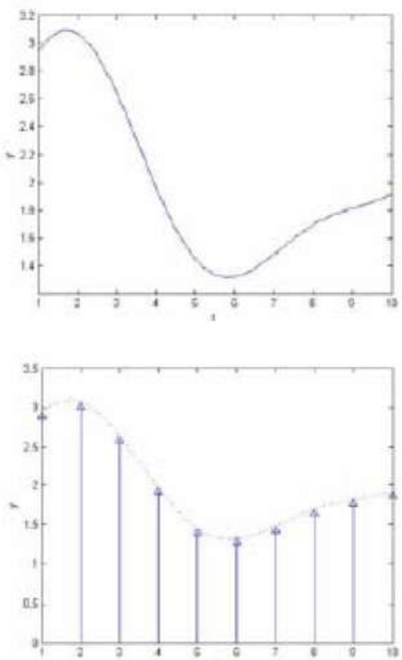

Affected by noise or EMI (Electromagnetic interference)



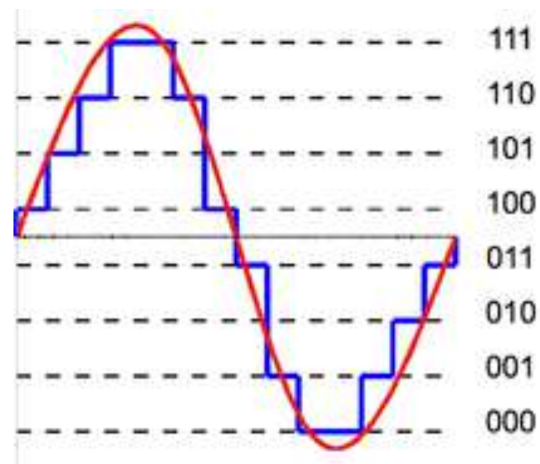



# Signal A/D (Analog-to-Digital)

- Sampling
  - From continuous signal to discrete signal
- PCM (Pulse Code Modulation)
  - Sampling → Quantization → Encoding



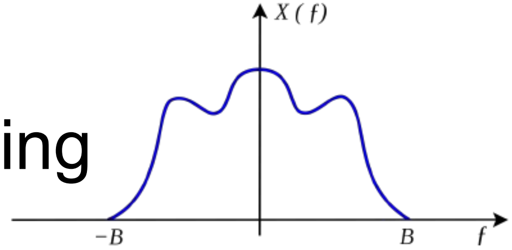
Uniform quantization




Binary encoding

# Signal A/D (Analog-to-Digital)

- Sampling
- Nyquist–Shannon sampling theorem
  (Harry Nyquist and Claude Shannon)




- Sufficient no-loss condition for sampling
  - Nyquist sampling rate: $2B$

- Usage example:
  - The frequency of human voice is mostly less than 5kHz, …

- Signal analysis
  - Time domain analysis
  - Frequency domain analysis
  - Time-Frequency domain analysis

# Time Domain Analysis

- The expectation ($\mu_x$) of a signal (or called mean)

$$\mu_x = E[x(t)] = \frac{1}{T}\lim\int_0^T x(t)dt$$

- Mean square ($A_{RMS}^2$) and root mean square (RMS) ($A_{RMS}$) of a signal

$$A_{RMS}^2 = E[x^2(t)] = \frac{1}{T}\lim\int_0^T x^2(t)dt$$

- Variance ($\sigma^2$) and standard deviation ($\sigma$) of a signal

$$\sigma^2 = E[(x(t)-\mu_x)^2] = \frac{1}{T}\lim\int_0^T (x(t)-\mu_x)^2 dt$$

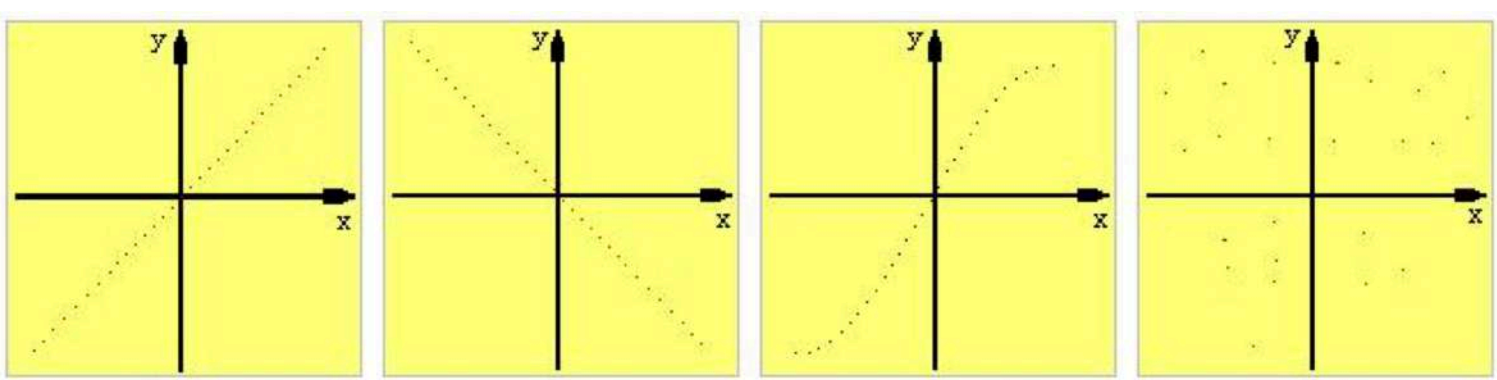
# Time Domain Analysis

- Covariance

$$cov(x,y)(= E\left[(x(t)-\mu_x)(y(t)-\mu_y)\right]$$

- Statistical correlation

$$\rho_{xy} = \frac{cov(x,y)}{\sigma_x \sigma_y} = \frac{E\left[(x(i)-\mu_x)(y(i)-\mu_y)\right]}{\sqrt[2]{E[(x(i)-\mu_x)^2]E\left[(y(i)-\mu_y)^2\right]}}$$



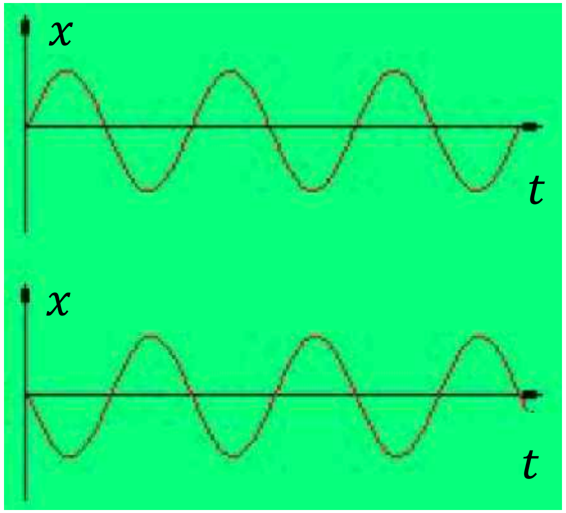

$\rho_{xy} = 1$ $\rho_{xy} = -1$ $0 \le \rho_{xy} \le 1$ $\rho_{xy} = 0$ Relationship?

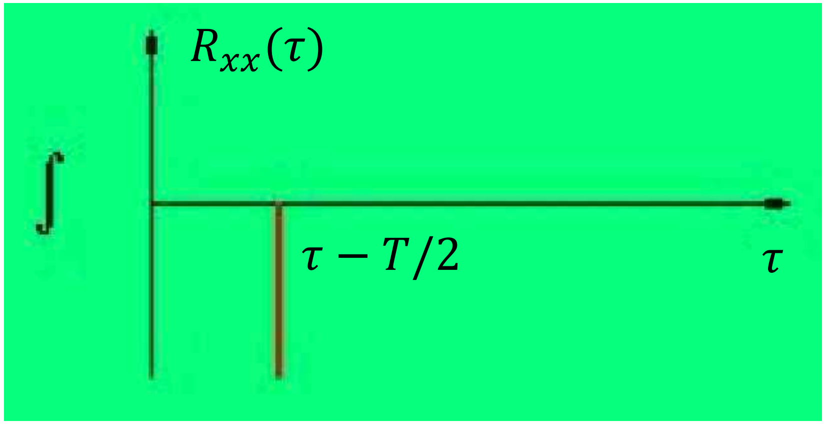
# Time Domain Analysis

- Correlation function for continuous signals

$$R_{xy}(\tau) = \lim_{T\to\infty} \int_{-T/2}^{T} x(t)y(t-\tau)$$

- Auto-correlation function $R_{xx}(\tau)$



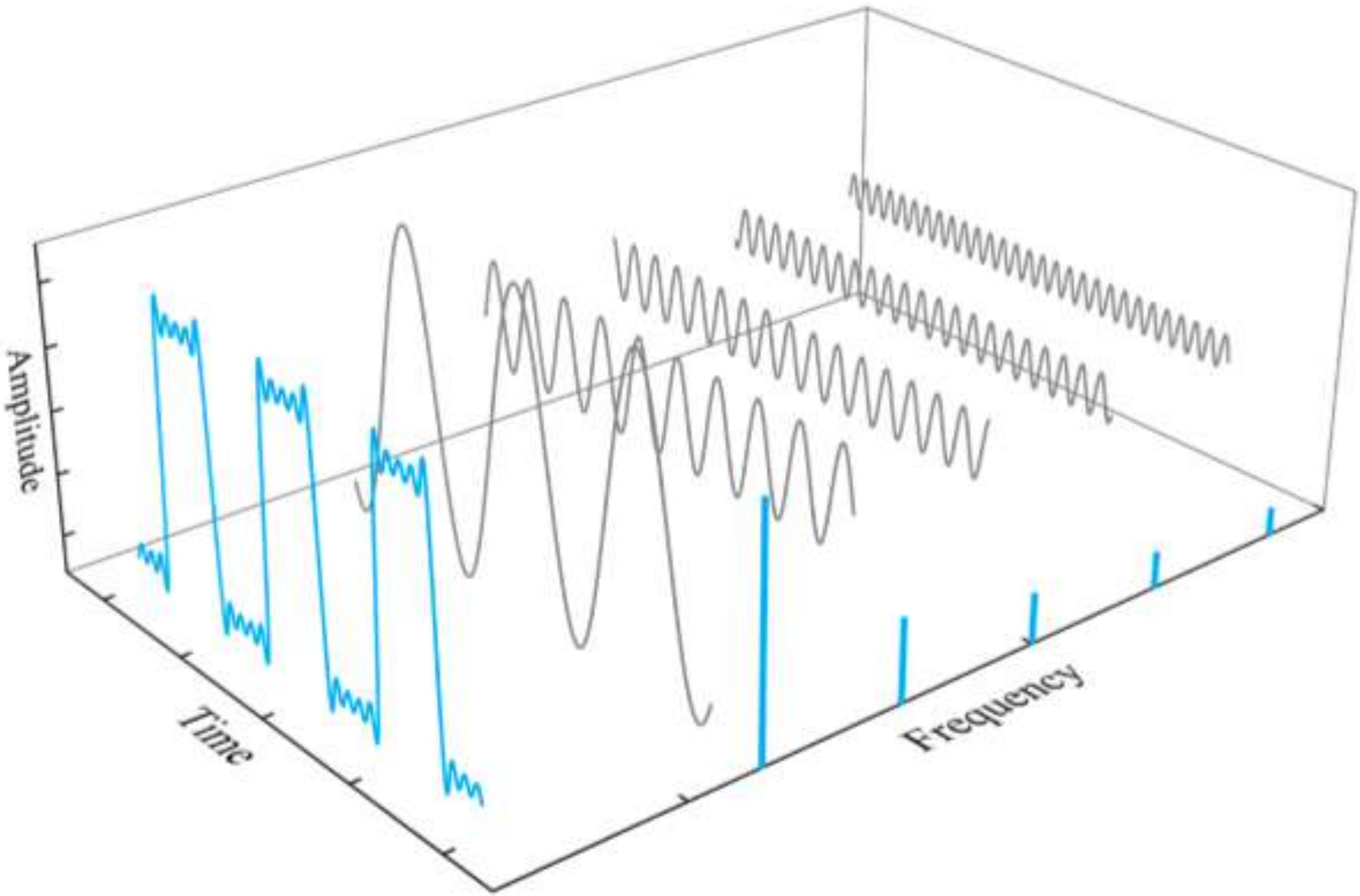




Similarity between two signals, or one signal with time shift

# Time Domain Analysis

- Time-domain operations for digital signals
  - Amplitude modifications $y[k] = a \sum x_m[k] + b$
  - Time modifications $y[k] = x[k - m]$
  - Down-sampling $y[k] = x[\lambda k]$
  - Up-sampling or interpolation
  - Cross-correlation ($\otimes$): $\mathrm{y}[\mathrm{k}] = \sum_{n=-\infty}^{\infty} x_1[n] x_2[n - k]$
  - Auto-correlation $\mathrm{y}[k] = \sum_{n=-\infty}^{\infty} x[n] x[n - k]$
  - Convolution (*): $\mathrm{y}[k] = \sum_{n=-\infty}^{\infty} x_1[n] x_2[k - n]$

# Signal Frequency Analysis



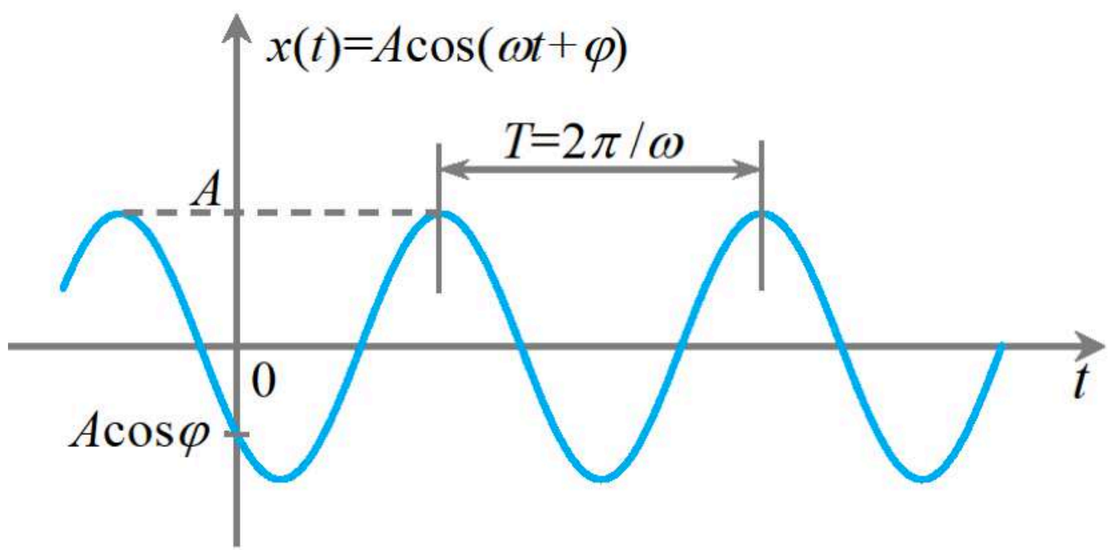
# Signal Frequency Analysis

- Frequency domain

- A typical signal: *sin* wave

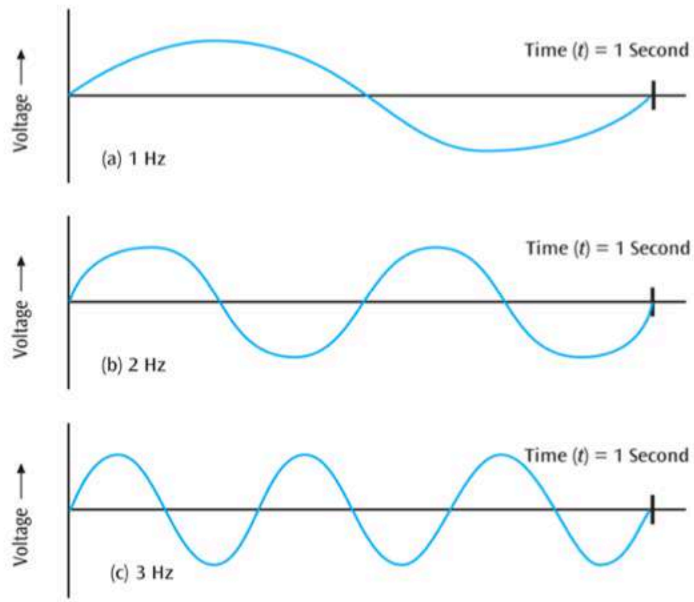
$$x(t) = A\cos(\omega t + \varphi)$$

Aptitude: $A$
Frequency: $f = \omega/2\pi$
Phase: $\varphi$



# Signal Frequency Analysis

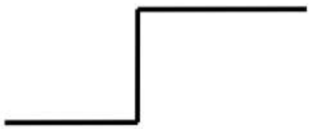
- Frequency of a signal




Constant-amplitude signal?



Step signal?



# Signal Frequency Analysis

- Fourier transform and inverse transform
  (under Dirichlet condition of convergence)

$$X(\omega) = \int_{-\infty}^{\infty} x(t)e^{-j\omega t}dt$$

$$x(t) = \int_{-\infty}^{\infty} X(\omega)e^{j\omega t}d\omega$$

- Fourier series expansion
  DFT (Discrete-time Fourier Transform)

$$x(t) = \sum_{k=-\infty}^{\infty} A_k \cos(k\omega_0 t + \varphi_k)\,,\ \omega_0=2\pi/T$$

Decomposes periodic complex signal to a (possibly infinite) set of simple sine waves;

Applicable for aperiodic signal, considering $T \to \infty$

# Signal Frequency Analysis

- Given Euler's formula

$$e^{j\theta} = cos(\theta) + jsin(\theta), \theta = \omega t, \cos(\omega t) = \frac{e^{j\omega t} + e^{-j\omega t}}{2}$$

$$Then: \ Acos(\omega t + \varphi) = \frac{A}{2} e^{j(\omega t + \varphi)} + \frac{A}{2} e^{-j(\omega t + \varphi)}$$

- Exponential form of Fourier series

$$x(t) = \sum_{k=-\infty}^{\infty} X_k \, e^{jk\omega_0 t}$$

where $X_k$ are complex numbers:

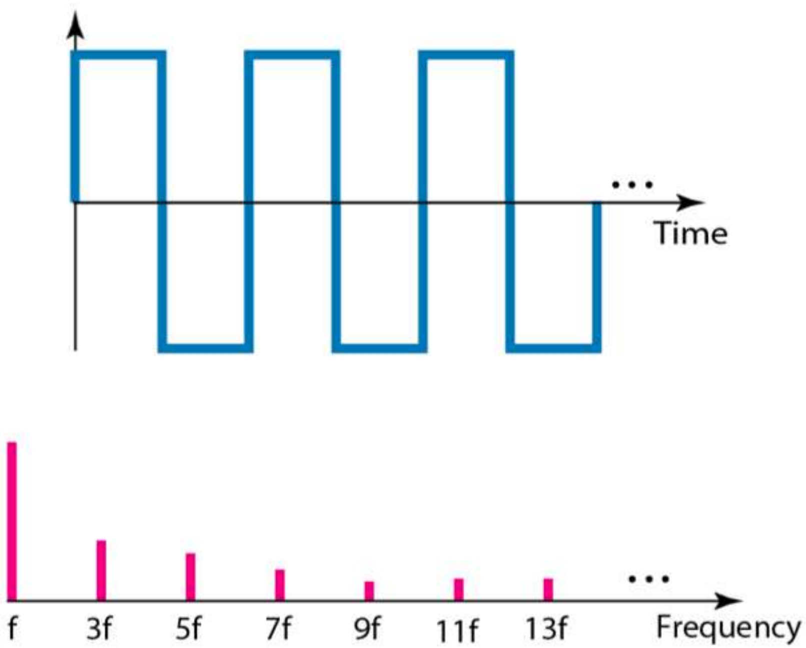
$$X_k = \frac{1}{T} \int_0^T x(t) \, e^{-jk\omega_0 t} dt$$

- For each frequency components:
  Frequencies $k\omega_0$; Amplitude $|X_k|$; Phase $arctan \frac{Im(X_k)}{Re(X_k)}$, atan2

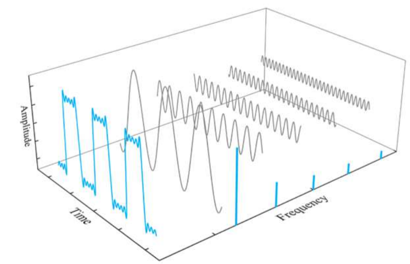
# Signal Frequency Analysis

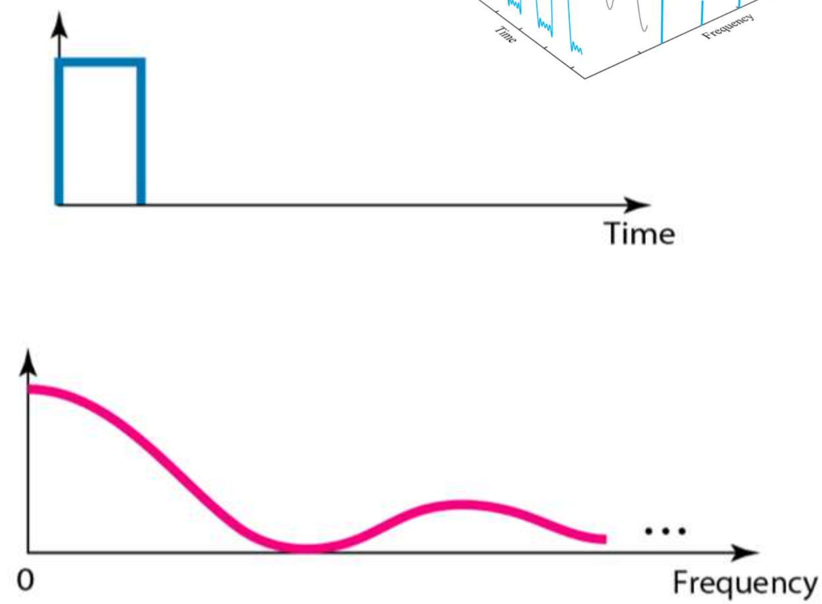
- DFT difference for periodic and aperiodic signal in Trigonometric series

$$x(t) = A_0 + \sum_{k=-\infty}^{\infty} A_k \cos(k\omega_0 t + \varphi_k)\,,\ \omega_0 = 2\pi/T$$




First/Second/… **harmonic** components





# Signal noise

- Naturally, sensor data is noisy.
  - Hardware filters
  - Algorithm filters

- Noise
  - A general term for all unwanted (probably immeasurable) modifications during signal capturing to processing process.
  - Wrong measurement doesn’t belong to noise.
- Noise types
  - Additive noise (White noise, Gaussian noise, Cauchy noise ...)
  - Multiplicative noise (multiplies or modulates the intended signal)
  - Quantization error (due to conversion from continuous to discrete values)
  - Phase noise (random time shifts in a signal)
  - et al.

# Signal noise

- White Gaussian noise
  - Good approximation of many real-world situations;
  - Mathematically tractable models;

- White: refers to "uniform power across the frequency".
- Gaussian: refers to "normal distribution in the time domain" with mean as zero.

- How ‘big’ is the noisy related to the signal?

# Signal noise

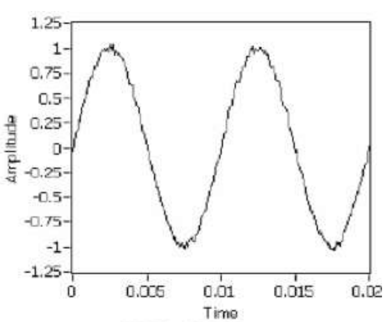
- Signal-to-noise ratio (SNR)

$$SNR = \frac{P_{signal}}{P_{noise}} = \left(\frac{A_{RMS,s}}{A_{RMS,n}}\right)^2$$

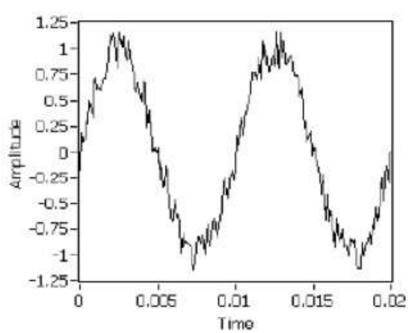
- Logarithmic decibel (dB) scale

$$P_{dB} = 10\log_{10} P$$

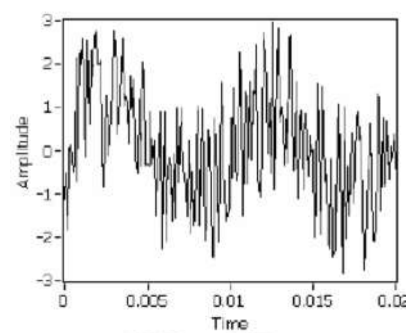
$$SNR_{dB} = 10\log_{10}\frac{P_{signal}}{P_{noise}} = 20\log_{10}\frac{A_{RMS,s}}{A_{RMS,n}}$$




SNR=26dB




SNR=14dB

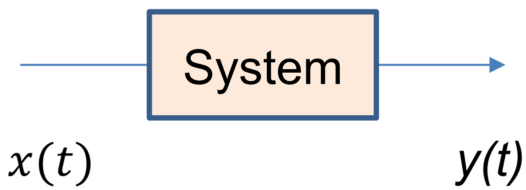


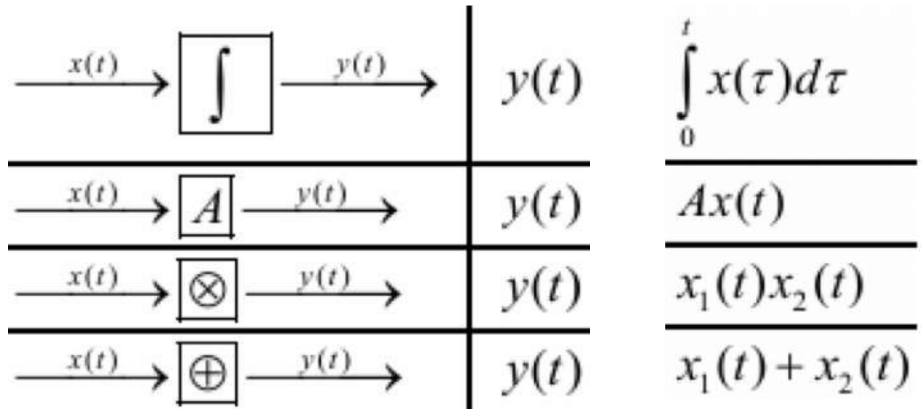

SNR = -6dB

# Digital Signal Processing Systems

- From signal to systems

examples

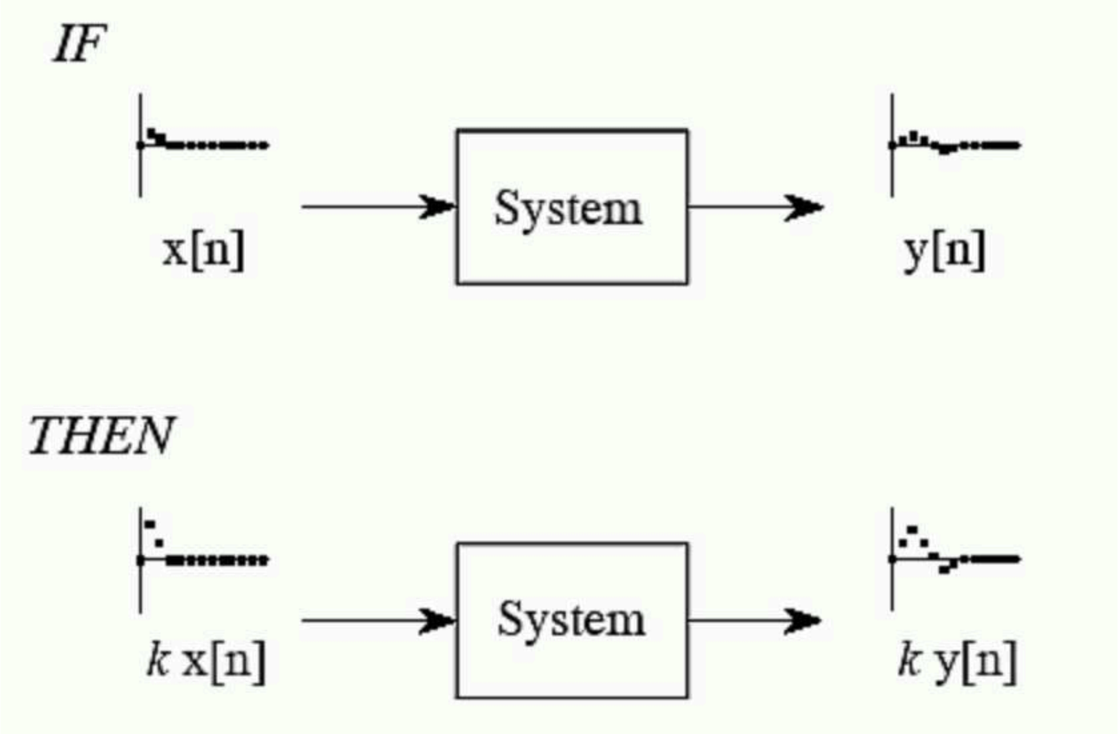



- Linear VS. Non-linear systems
- Characteristics of linear system
  - Homogeneity
  - Additivity
- Linear Time-invariant (LTI)

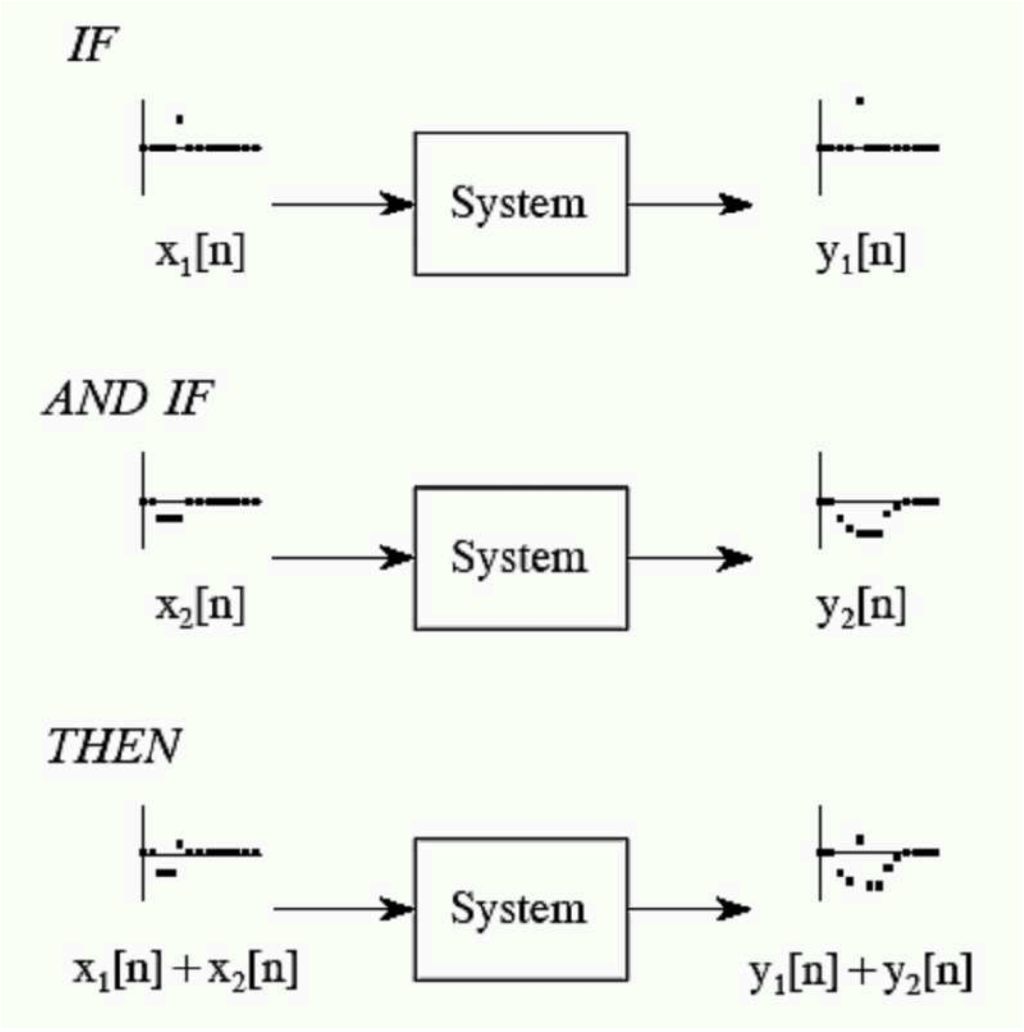
# Digital Signal Processing Systems

- Homogeneity of linear systems



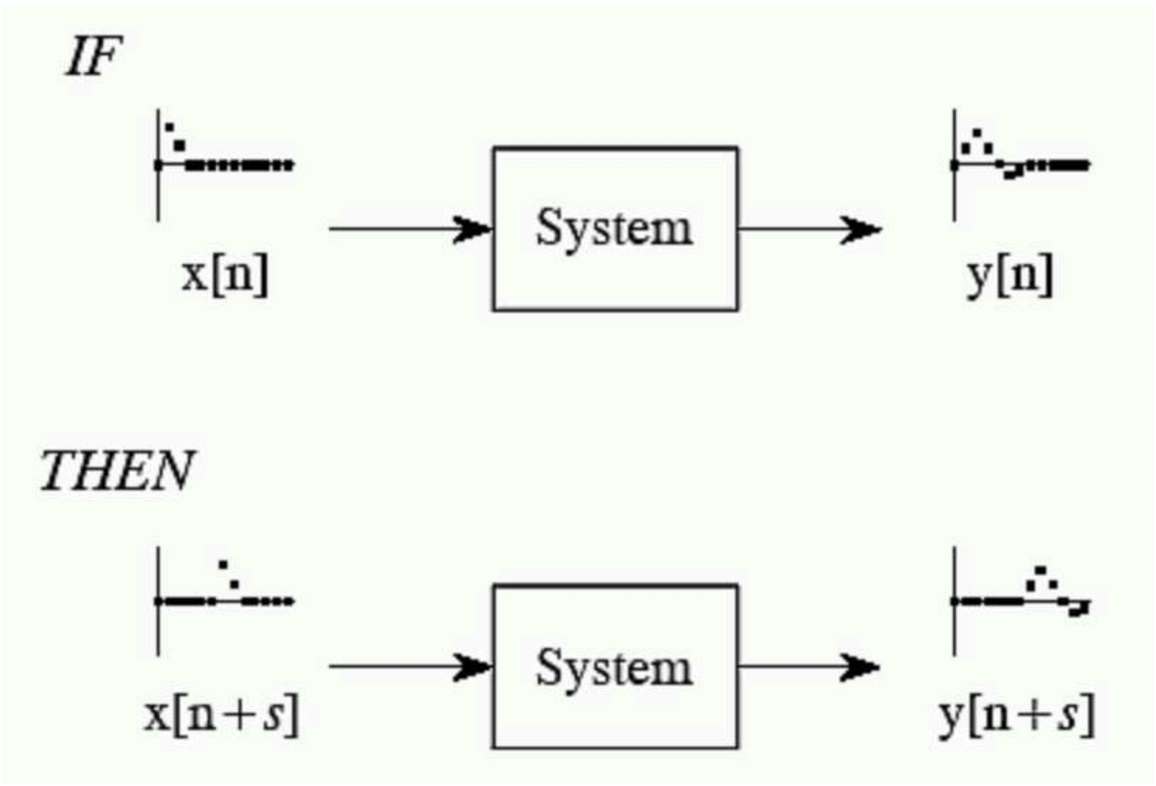
# Digital Signal Processing Systems

- Additivity of linear systems



# Digital Signal Processing Systems

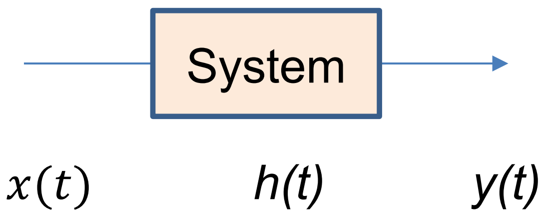
- Time-invariant systems




Important !
The characteristics of the system do not change with time.

# Digital Signal Processing Systems

- System analysis

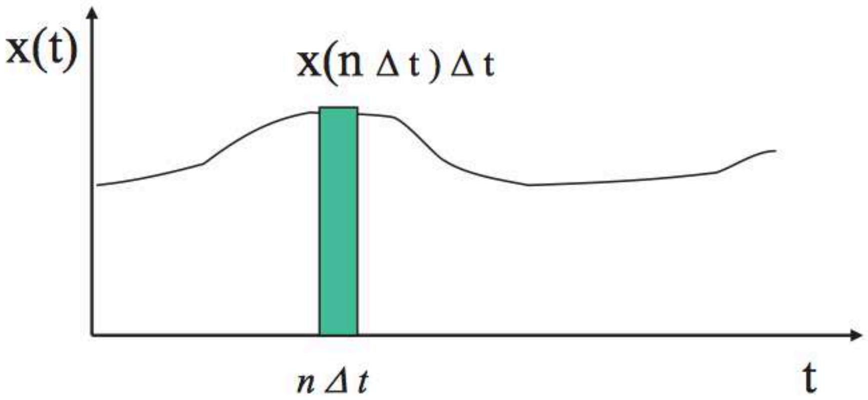


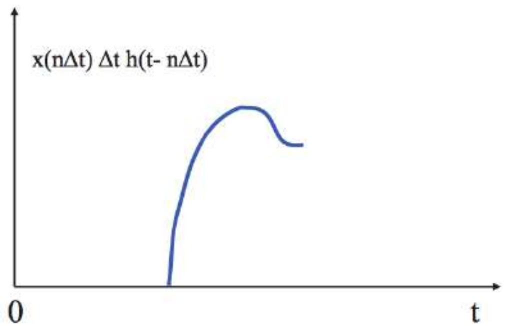

*h(t)* ?

- How to mathematically describe a system?
- How to design such a system?

# Digital Signal Processing Systems

- System response

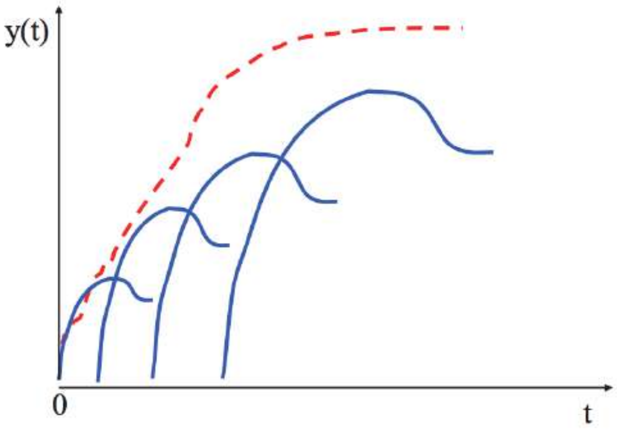



Response:

$$x(n\Delta t)\Delta t\ h(t-n\Delta t)$$

$$y(t)=\sum_{n=0}^{\infty}x(n\Delta t)\Delta t\ h(t-n\Delta t)$$




Signal convolution:

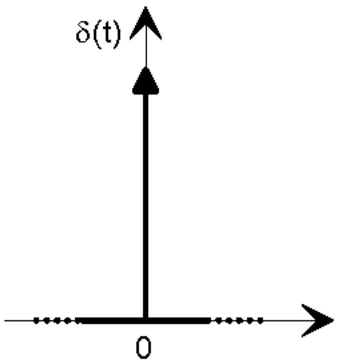
$$y(t)=x(t)*h(t)$$
$$=\int_{-\infty}^{\infty}x(\tau)h(t-\tau)d\tau$$

# Digital Signal Processing Systems

- (Unit) Delta function (impulse signal, Paul Dirac)

$$\delta(t-\tau_0)=0, x\neq 0$$

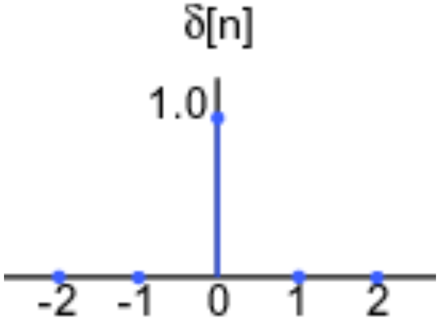
$$\lim_{\varepsilon\to 0}\int_{\tau_0-\varepsilon}^{\tau_0+\varepsilon}\delta(t-\tau_0)dt=1$$




- Characteristic

$$x(\tau_0)=\int_{-\infty}^{\infty}x(t)\delta(t-\tau_0)dt$$

$$x[n]=\sum_{k=-\infty}^{\infty}x[k]\delta(n\ -k)$$




- $h(t)$ is defined as impulse response, which is the system response when input signal is $\delta(t)$

# Digital Signal Processing Systems

- We have seen signal can be characterized by frequency content (pros?)
- LTI system analysis
  - Time-domain impulse response $h(t)$
  - Frequency response --- $H(\omega)$?
- For system analysis, introduce dampening factor, and Laplace transform and $z$ transform:

$$L(\omega) = \int_{-\infty}^{\infty} x(t) e^{-(\sigma + j\omega)t} dt \ \rightarrow \ L(s) = \int_{-\infty}^{\infty} x(t) e^{-st} dt, where\ s = \sigma + j\omega$$

For discrete signal: $X(z) = \sum_{-\infty}^{\infty} x[n] z^{-n}$ ,

$$where\ z = e^{sT} = r\ e^{j\omega}$$

# Digital Signal Processing Systems

- All three transforms convert time-domain convolutions to polynomial equations

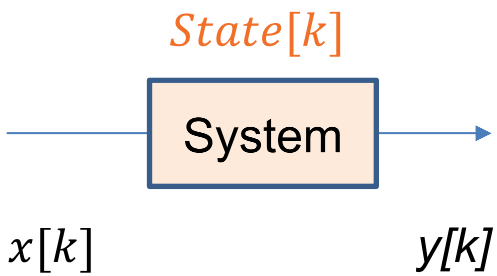
$$y(t) = x(t) * h(t) = \int_{-\infty}^{\infty} x(\tau)h(t-\tau)d\tau$$

$$Y(\omega) = H(\omega)X(\omega),\ Y(s) = H(s)X(s),\ Y(z) = H(z)X(z)$$

- Why Laplace transform and $z$ transform?
  - Complex frequency-domain for Stability and Causality analysis

# Digital Filter Design

- State-space filter




Using dynamic model
e.g.: Kalman filter

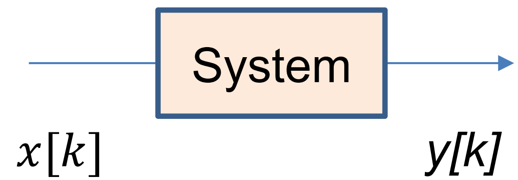
$$\bar{\mu}_t = A_t \mu_{t-1} + B_t u_t$$
$$\bar{\Sigma}_t = A_t \Sigma_{t-1} A_t^T + R_t$$

$$K_t = \bar{\Sigma}_t C_t^T (C_t \bar{\Sigma}_t C_t^T + Q_t)^{-1}$$
$$\mu_t = \bar{\mu}_t + K_t (z_t - C_t \bar{\mu}_t)$$
$$\Sigma_t = (I - K_t C_t) \bar{\Sigma}_t$$

- Conventional digital filters

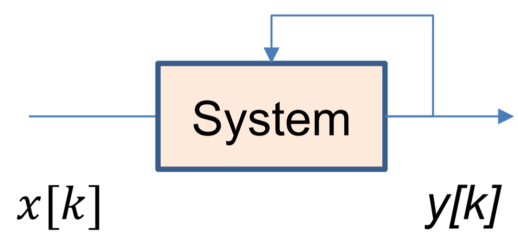
Finite Impulse Response (FIR) filters:

$$y[k] = \sum_{n=0}^{N} b_n x[k-n]$$




Infinite Impulse Response (IIR) filters:

$$y[k] = \sum_{n=0}^{N} b_n x[k-n] + \sum_{m=0}^{M} a_m y[k-m]$$



# Digital Filter Design

- FIR Filters
  - Pros:
    - Inherently stable
    - Linear phase characteristics
  - Cons:
    - Need lots of memory and math terms required
- IIR Filters
  - Pros:
    - Very efficient in term of resources
  - Cons:
    - Inherently less stable

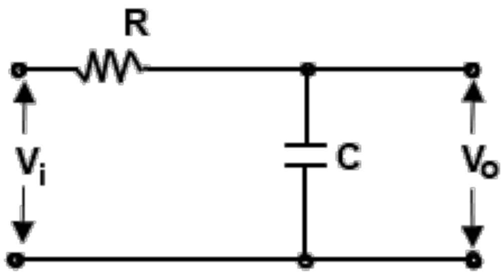
Design approaches:

Frequency sampling design
Fourier transform design

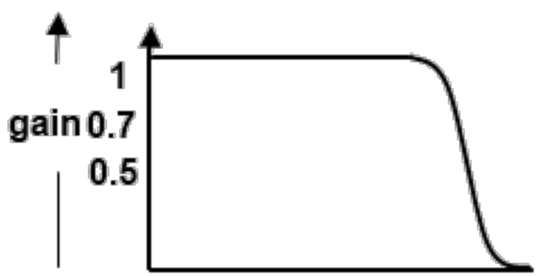
Bilinear transformation
Pole zero placement

# Digital Filter Design

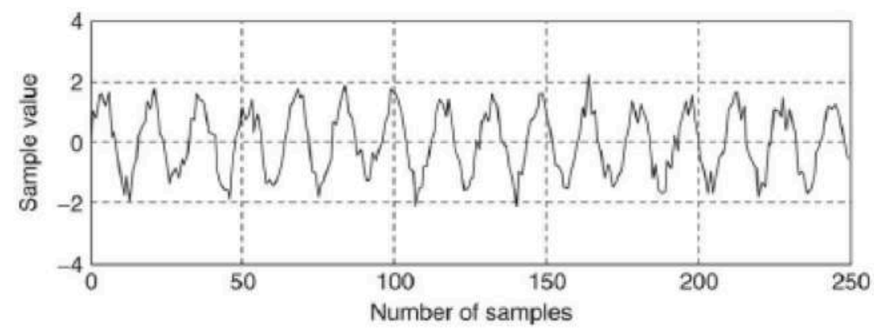
- Example: low pass filter design

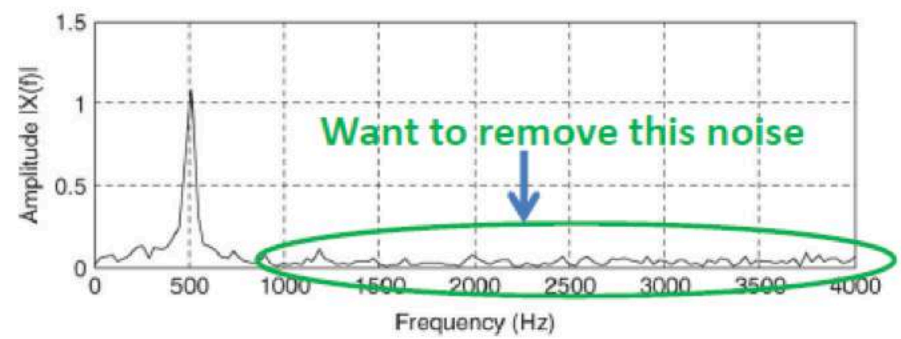



(a)RC low Pass Filter Circuit




(b) Frequency ResponseCurve



# Digital Filter Design

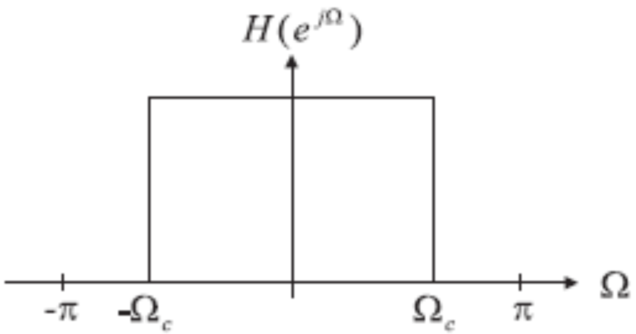
- A simple example of digital filter:

$$y[k] = \frac{1}{4}(x[k] + 2x[k-1] + x[k-2])$$

- (ideal) FIR low pass filter (LPF) design [1]

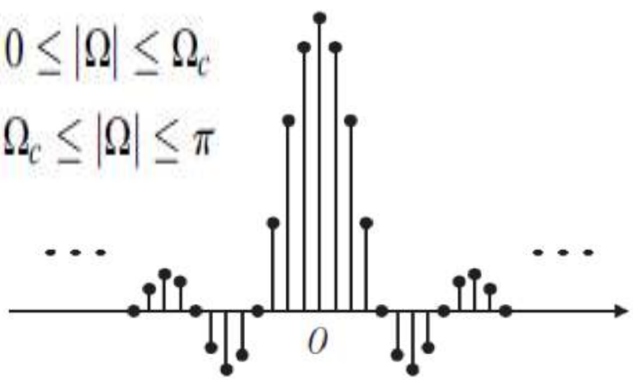
$$y[k] = \sum_{n=0}^{N} b_n x[k-n]$$

$b_n$: filter coefficients (aka: kernel)




$$H(e^{j\Omega}) = \begin{cases} 1, & 0 \le |\Omega| \le \Omega_c \\ 0, & \Omega_c \le |\Omega| \le \pi \end{cases}$$

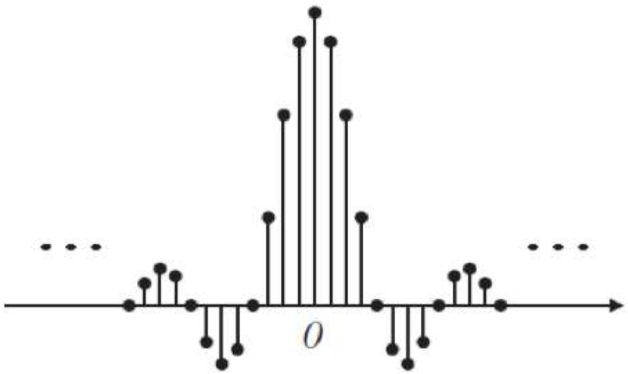
Inverse FFT




Impulse response $h_n$

# Digital Filter Design

- (ideal) FIR low pass filter design [1]




Impulse response

- $h_n$ → z transformation H(z)

$$H(z) = h(M)z^{M} + \cdots + h(1)z^{1} + h(0) + h(1)z^{-1} + \cdots + h(M)z^{-M}$$

Symmetric

By After truncating 2M+1 major components using the coefficient symmetry, where $h_n$ is just a shift of $b_n$ for causal design.

# Digital Filter Design

| Filter | Type Ideal Impulse Response $h(n)$ (noncausal FIR coefficients) |
|---|---|
| Lowpass: | $h(n) = \begin{cases} \dfrac{\Omega_c}{\pi} & \text{for} \quad n = 0 \\ \dfrac{\sin(\Omega_c n)}{n\pi} & \text{for} \quad n \neq 0 \end{cases} \quad -M \leq n \leq M$ |
| Highpass: | $h(n) = \begin{cases} \dfrac{\pi - \Omega_c}{\pi} & \text{for} \quad n = 0 \\ -\dfrac{\sin(\Omega_c n)}{n\pi} & \text{for} \quad n \neq 0 \end{cases} \quad -M \leq n \leq M$ |
| Bandpass: | $h(n) = \begin{cases} \dfrac{\Omega_H - \Omega_L}{\pi} & \text{for} \quad n = 0 \\ \dfrac{\sin(\Omega_H n)}{n\pi} - \dfrac{\sin(\Omega_L n)}{n\pi} & \text{for} \quad n \neq 0 \end{cases} \quad -M \leq n \leq M$ |
| Bandstop: | $h(n) = \begin{cases} \dfrac{\pi - \Omega_H + \Omega_L}{\pi} & \text{for} \quad n = 0 \\ -\dfrac{\sin(\Omega_H n)}{n\pi} + \dfrac{\sin(\Omega_L n)}{n\pi} & \text{for} \quad n \neq 0 \end{cases} \quad -M \leq n \leq M$ |

[1]

# Digital Filter Design

- (ideal) FIR low pass filter design [1]

- Example: Design a 3-tap FIR LPF with cut-off frequency of 800 Hz and a sampling rate of 8,000 Hz using the Fourier transform method.

Normalized cut-off frequency ⇒

$$\Omega_c = 2\pi f_c T_s = 2\pi \times 800/8,000 = 0.2\pi \text{ radians}$$

3-tap filter ⇒ $2M + 1 = 3$ ⇒ $M = 1$

⇒ $h(n)\ for\ n\ from\ -M\ to\ M$ ⇒ $n = -1, 0, 1,$

# Digital Filter Design

- (ideal) FIR low pass filter design [1]

filter coefficients → $h(0) = \frac{\Omega_c}{\pi}$ for $n = 0$

From previous slide table

and $h(n) = \frac{\sin(\Omega_c n)}{n\pi} = \frac{\sin(0.2\pi n)}{n\pi}$ for $n \neq 1$

compute coefficients → $h(0) = \frac{0.2\pi}{\pi} = 0.2$

and $h(1) = \frac{\sin[0.2\pi \times 1]}{1 \times \pi} = 0.1871$

Using symmetry → $h(-1) = h(1) = 0.1871$

# Digital Filter Design

- (ideal) FIR low pass filter design [1]

Delaying h(n) by M = 1 sample

$$\Rightarrow \quad b_n = h(n - M) \quad \text{for } n = 0, 1, \ldots, 2M.$$

$$\Rightarrow \quad \begin{cases} b_0 = h(0-1) = h(-1) = 0.1871 \\ b_1 = h(1-1) = h(0) = 0.2 \\ b_2 = h(2-1) = h(1) = 0.1871 \end{cases}$$

FIR low pass filter: transfer function

$$H(z) = 0.1871 + 0.2z^{-1} + 0.1871z^{-2} \Rightarrow \frac{Y(z)}{X(z)} = H(z) = 0.1871 + 0.2z^{-1} + 0.1871z^{-2}$$

$$\Rightarrow \quad Y(z) = 0.1871X(z) + 0.2z^{-1}X(z) + 0.1871z^{-2}X(z)$$

# Digital Filter Design

- (ideal) FIR low pass filter design [1]

- Further discussion
  - Undesirable Gibbs oscillations
  - Solution: window functions

1. Rectangular window:

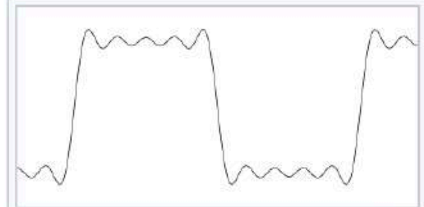
$$w_{rec}(n) = 1, \; -M \leq n \leq M$$

2. Triangular (Bartlett) window:

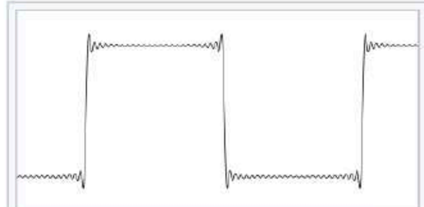
$$w_{tri}(n) = 1 - \frac{|n|}{M}, \; -M \leq n \leq M$$

3. Hanning window:

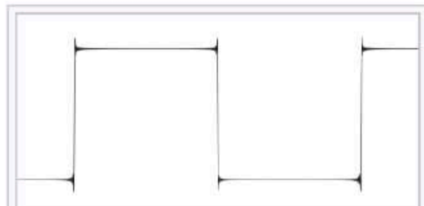
$$w_{han}(n) = 0.5 + 0.5\cos\left(\frac{n\pi}{M}\right), \; -M \leq n \leq M$$



Functional approximation of square wave using 5 harmonics



Functional approximation of square wave using 25 harmonics



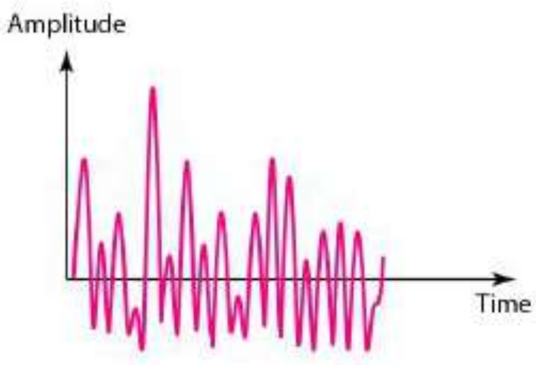
Functional approximation of square wave using 125 harmonics

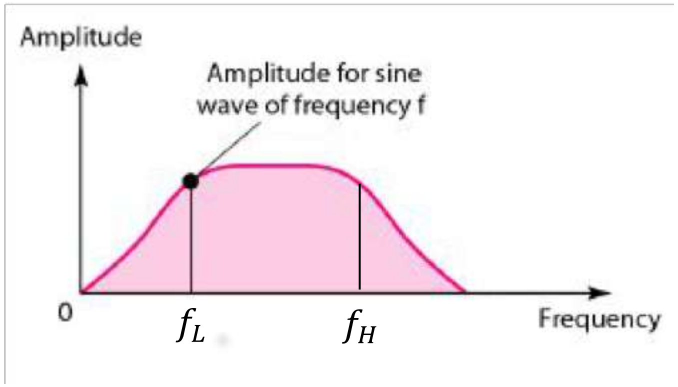
Applying the window sequence $w(n)$ to the filter coefficients

$$h_w(n) = h(n) \cdot w(n)$$

# Spectrum in Frequency Domain

- Frequency spectrum to bandwidth

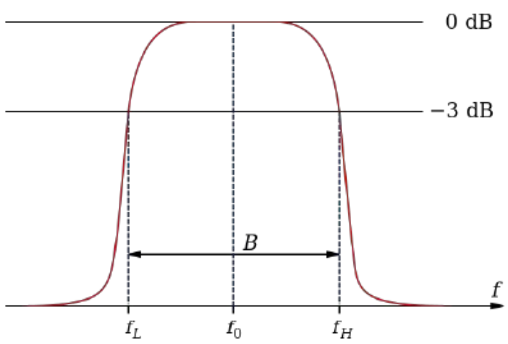


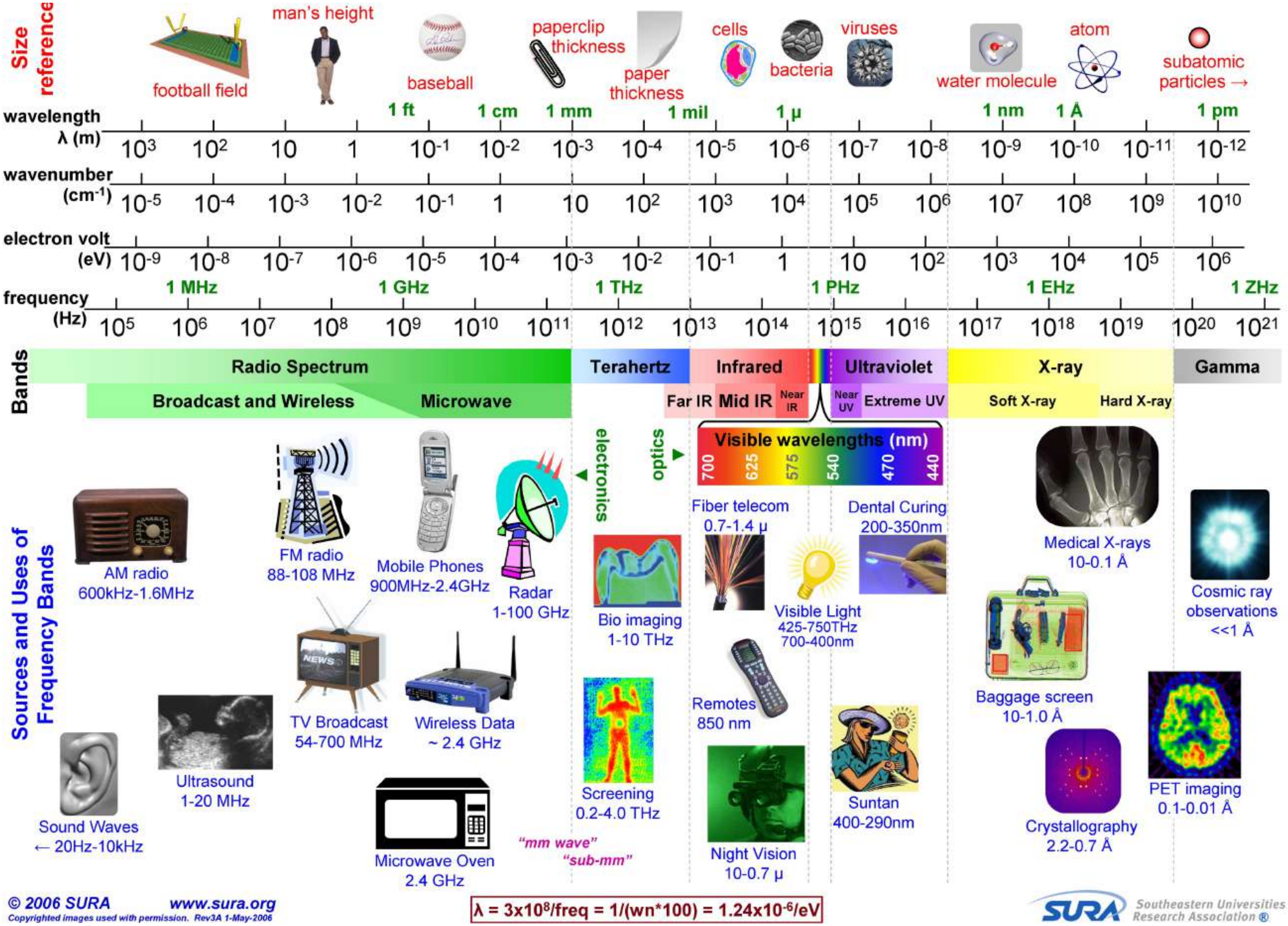

Bandwidth

Effective bandwidth

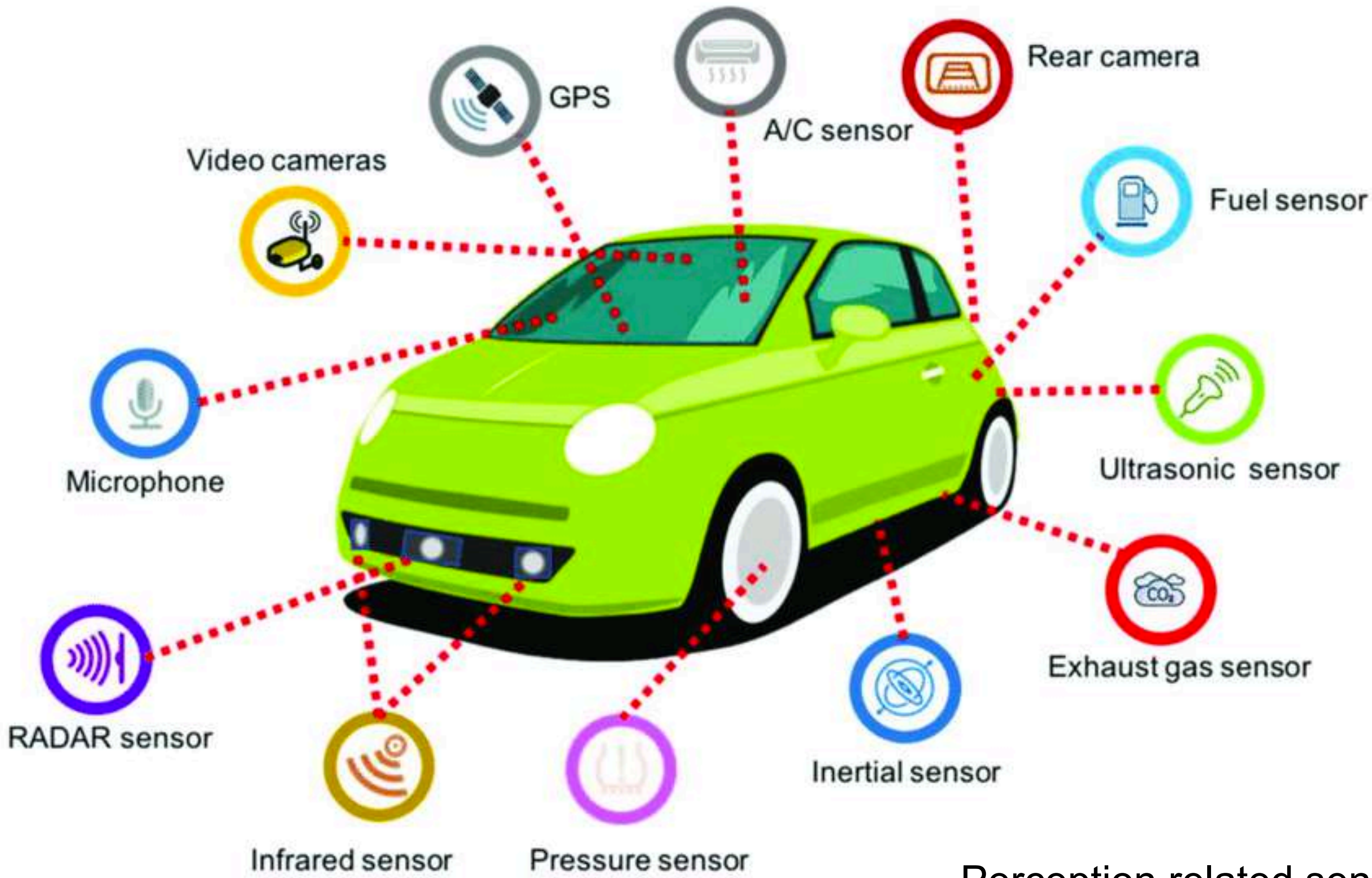
$$dB = 10\log_{10}\frac{P_{f_{L\sim H}}}{P_s}$$



# Electromagnetic Spectrum



# Vehicle Sensors



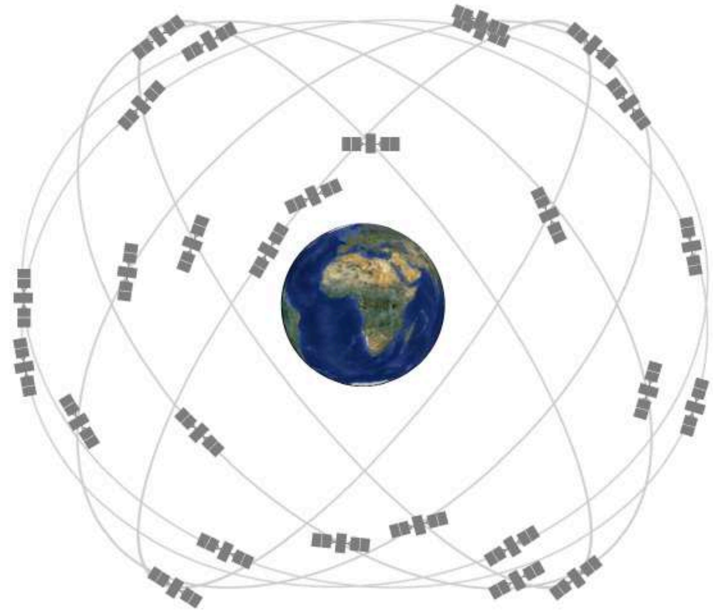

Perception related sensors

# Vehicle Sensors

- GPS (Global Positioning System)

- A constellation of 24 satellites (+several spares)

- Broadcast time;
  identity;
  orbital parameters (latitude, longitude, altitude);



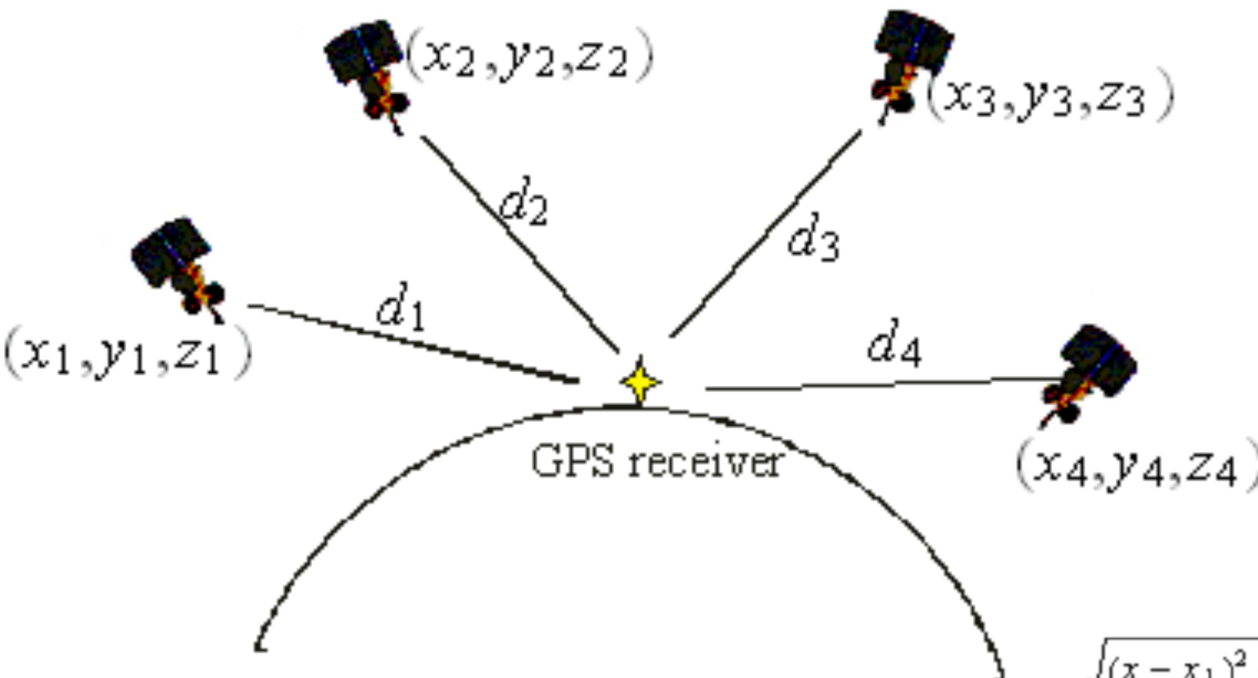
Space Segment

https://www.gps.gov

- Carriers - there are two carrier radio waves:
  - L1, with frequency 1575.42 MHz
  - L2, with frequency 1227.6 MHz

# Vehicle Sensors

- GPS (Global Positioning System)




Triangulation

$$\sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2}+ct_B=d_1$$

$$\sqrt{(x-x_2)^2+(y-y_2)^2+(z-z_2)^2}+ct_B=d_2$$

$$\sqrt{(x-x_3)^2+(y-y_3)^2+(z-z_3)^2}+ct_B=d_3$$

$$\sqrt{(x-x_4)^2+(y-y_4)^2+(z-z_4)^2}+ct_B=d_4$$

# Vehicle Sensors

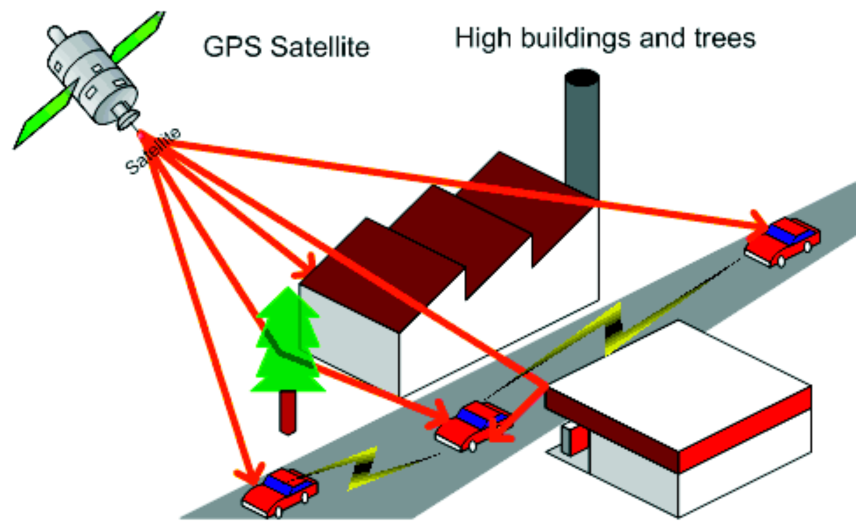
- GPS (Global Positioning System)

- Spherical coordinates
  - latitude
  - longitude
  - altitude (above sea level)

Expected errors:
ionospheric range error
tropospheric range error
satellite clock range error
receiver clock range error
multipath error
noise

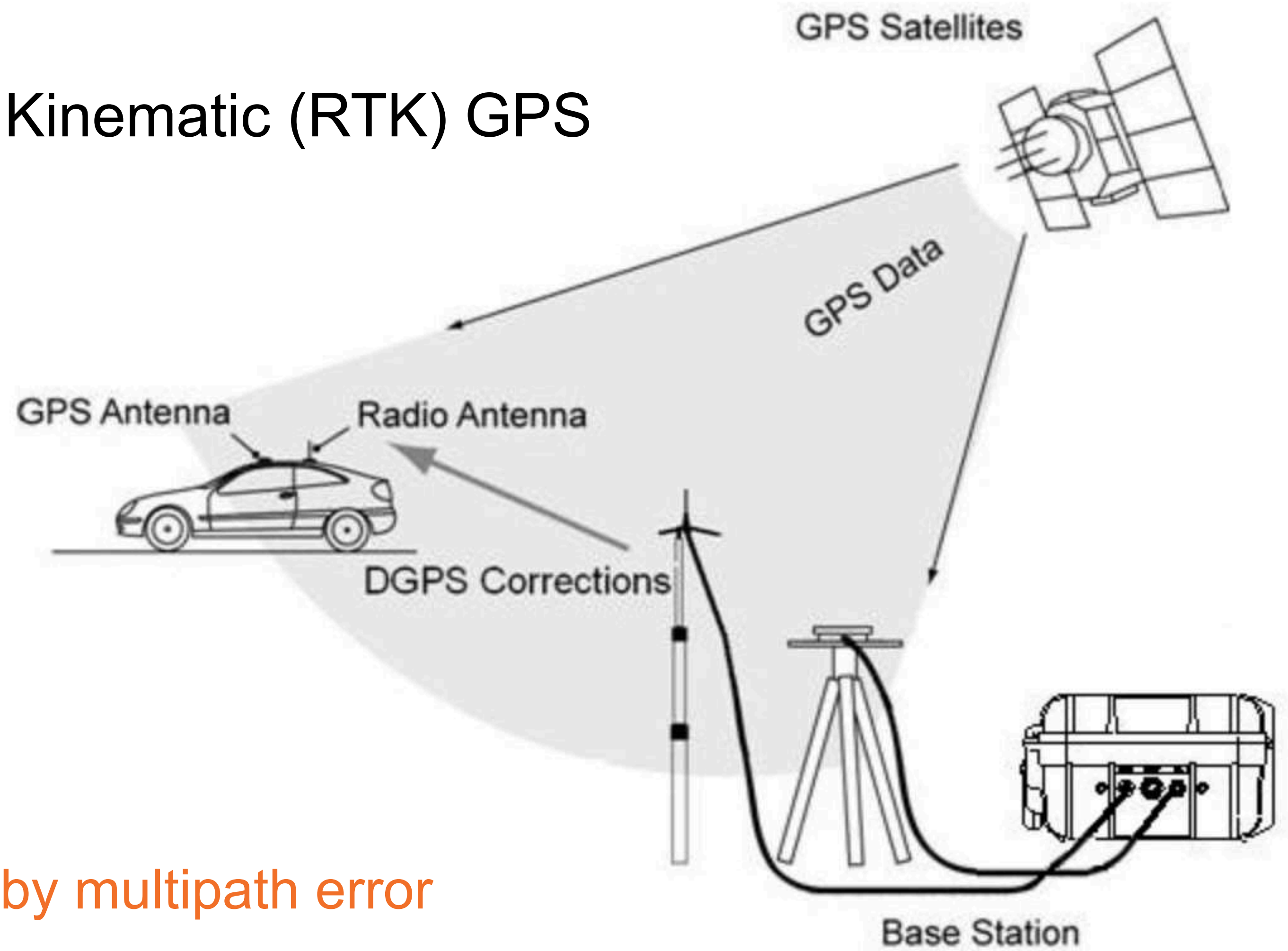
- PPS - Precise Positioning Service
  - uses multiple signals
  - for military use only

- DGPS - Differential GPS
  - 2 receivers
  - 1 known fixed position



# Vehicle Sensors

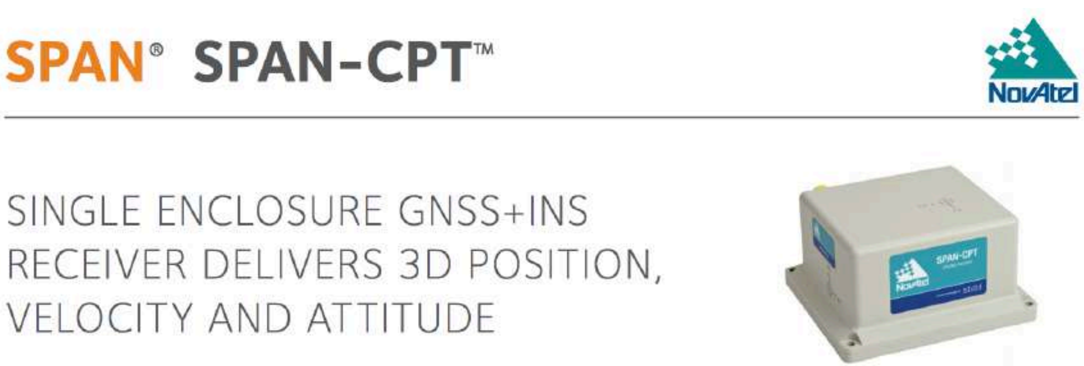
- GPS (Global Positioning System)
- Real-Time Kinematic (RTK) GPS




Still degraded by multipath error

# Vehicle Sensors

- **GNSS** global geo-spatial positioning system
  - Global Navigation Satellite System (GNSS) with global coverage.
- GNSS systems:
  - GPS, GLONASS, Galileo, Beidou and other regional systems.
- **GNSS+INS fusion**
  - Example: NovAtel SPAN-CPT GNSS-INS



# Vehicle Sensors

- GNSS+INS
- NovAtel SPAN-CPT

**SPAN SYSTEM PERFORMANCE[1]**

**Horizontal Position Accuracy (RMS)**

| | |
|---|---|
| Single point L1/L2 | 1.2 m |
| NovAtel CORRECT™ | |
| » SBAS[2] | 60 cm |
| » DGPS | 40 cm |
| » PPP[3] | 4 cm |
| » RTK | 1 cm + 1 ppm |

**Data Rate**

| | |
|---|---|
| GPS measurement | 20 Hz |
| GPS position | 20 Hz |
| IMU measurement | 100 Hz |
| INS solution | Up to 100 Hz |

**Time Accuracy[4]** 20 ns RMS

**Max Velocity[5]** 515 m/s

**IMU PERFORMANCE[6]**

**Gyroscope Performance**

| | |
|---|---|
| Gyro technology | FOG |
| Output range | ±375°/s |
| Bias | 20°/hr |
| Bias stability | ±1°/hr |
| Scale factor | 1500 ppm |
| Angular random walk | 0.0667°/√hr (max) |

**Accelerometer Performance**

| | |
|---|---|
| Range | ±10 g |
| Bias | 50 mg |
| Bias stability | ±0.75 mg |
| Scale factor | 4000 ppm |

**PHYSICAL AND ELECTRICAL**

**Dimensions** 152 x 168 x 89 mm

**Weight** 2.28 kg

**Power**

| | |
|---|---|
| Power consumption | 16 W max |
| Input voltage | +9 to +18 VDC |

**Antenna Port Power Output**

| | |
|---|---|
| Output voltage | +5 VDC |
| Maximum current | 100 mA |

**Connectors**

| | |
|---|---|
| Power and I/O | MIL-DTL-38999 Series 3 |
| Antenna Input | TNC Female |

**COMMUNICATION PORTS**

| | |
|---|---|
| RS-232 UART COM | 2 |
| USB Device | 1 |
| CAN | 1 |
| Event Input Trigger | 1 |
| Configurable PPS | 1 |

**ENVIRONMENTAL**

**Temperature**

| | |
|---|---|
| Operating | -40°C to +65°C |
| Storage | -50°C to +80°C |

**Humidity** 95% non-condensing

**Waterproof** MIL-STD-810F, 506.4, Procedure I

**INCLUDED ACCESSORIES**

- Combined I/O and power cable

**OPTIONAL ACCESSORIES**

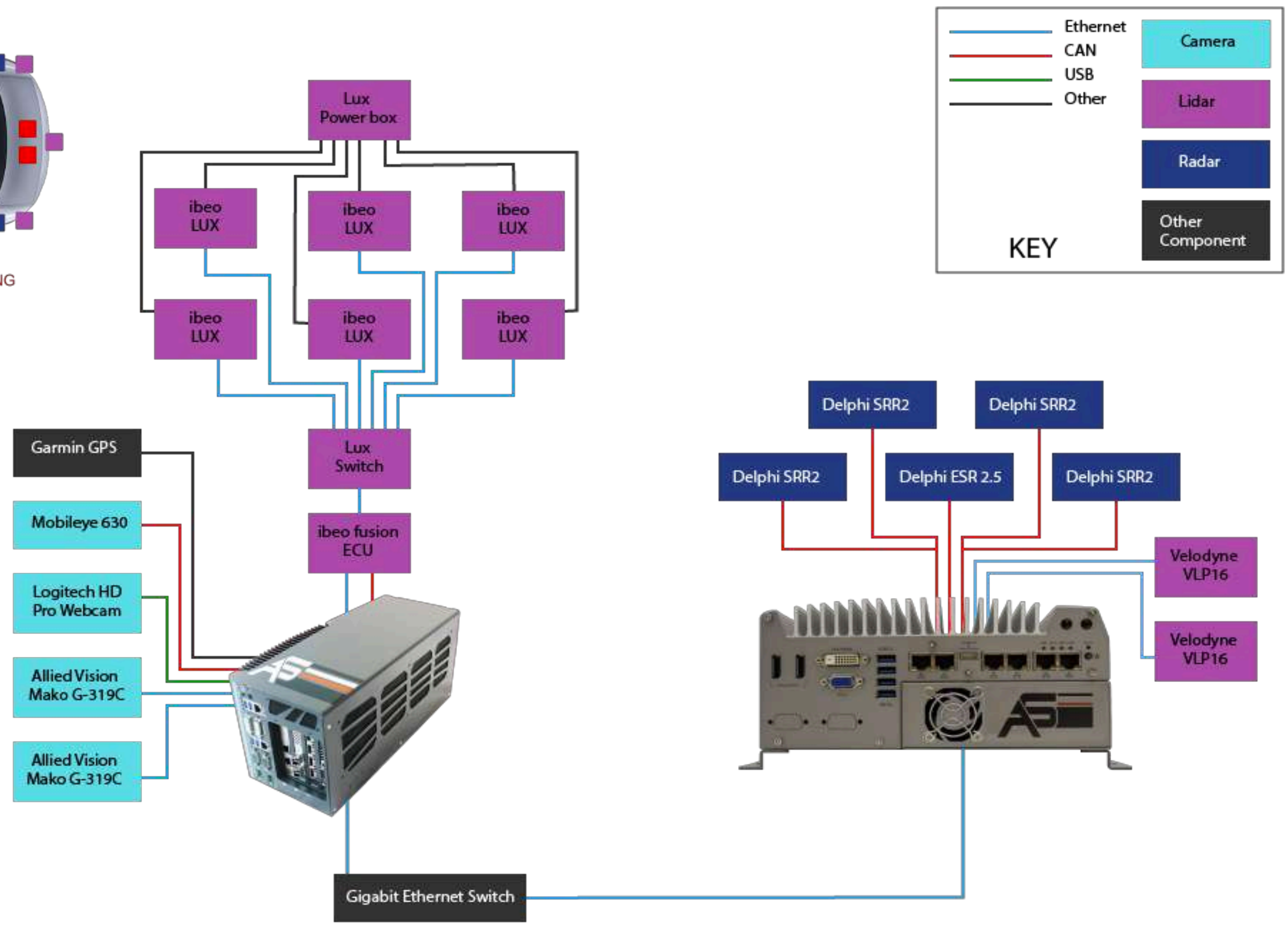
- GPS-700 series antennas (dual-frequency required)
- ANT series antennas (dual-frequency required)
- RF cables–5, 10 and 30 m lengths
- Inertial Explorer post-processing software

**Optional Dual Antenna[7]**

| Baseline | Accuracy |
|---|---|
| 0.5 m | 0.4° |
| 1.0 m | 0.2° |
| 2.0 m | 0.1° |

# Vehicle Sensors

- Perception kit configuration example

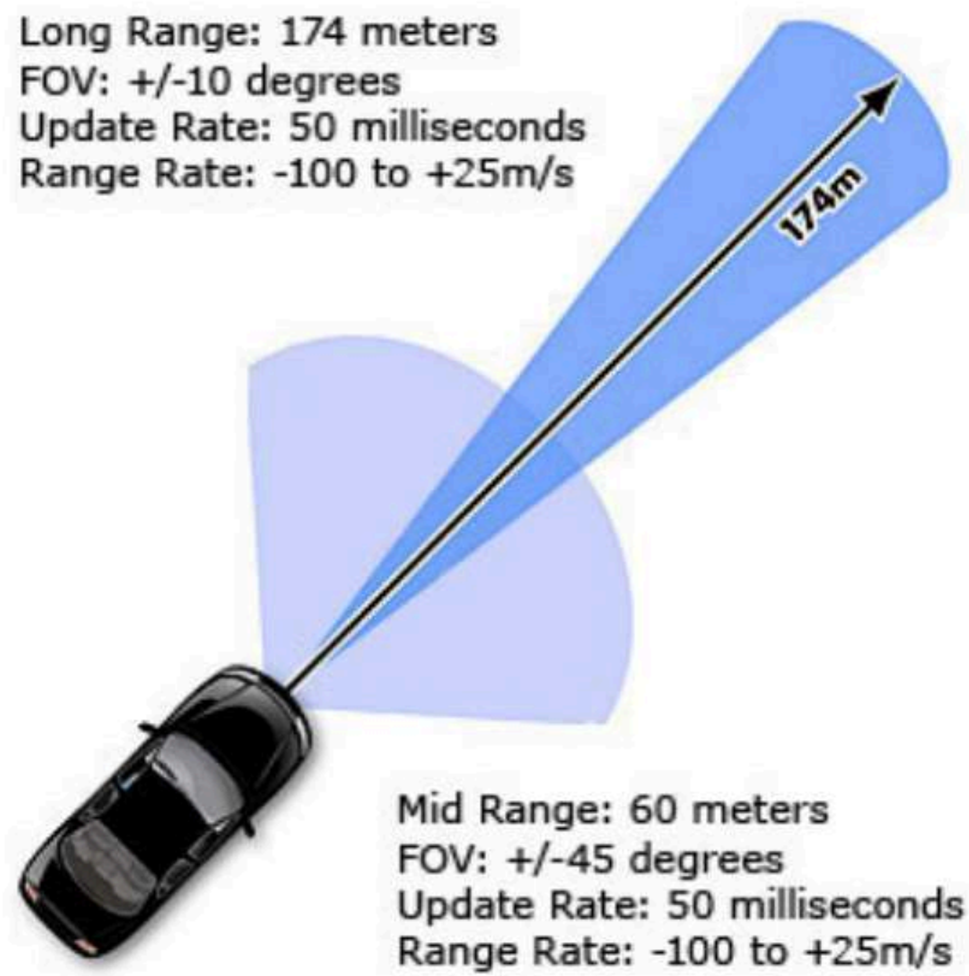



# Vehicle Sensors

- Delphi ESR 2.5 Radar

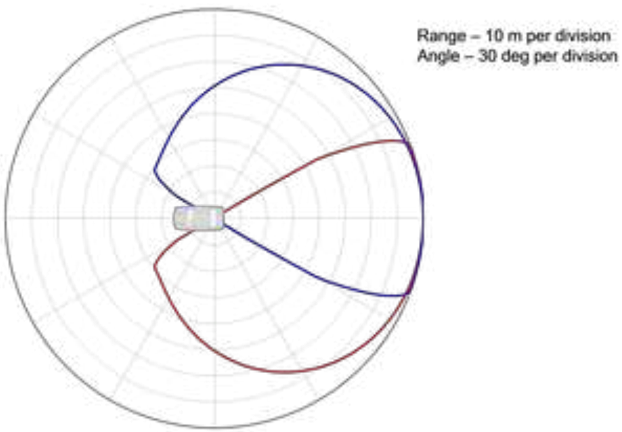
- DEL-ESR-2.5 -24VDC+

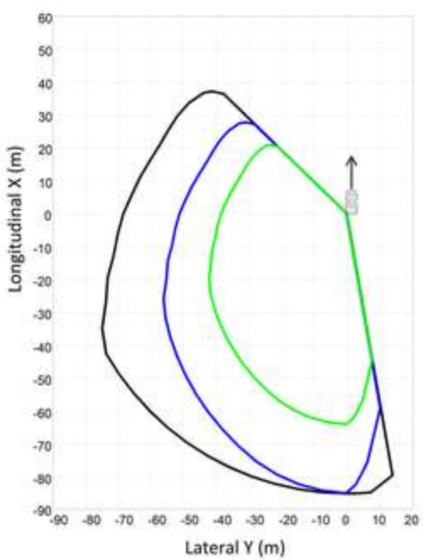
- Delphi's multimode Electronically Scanning RADAR (ESR)

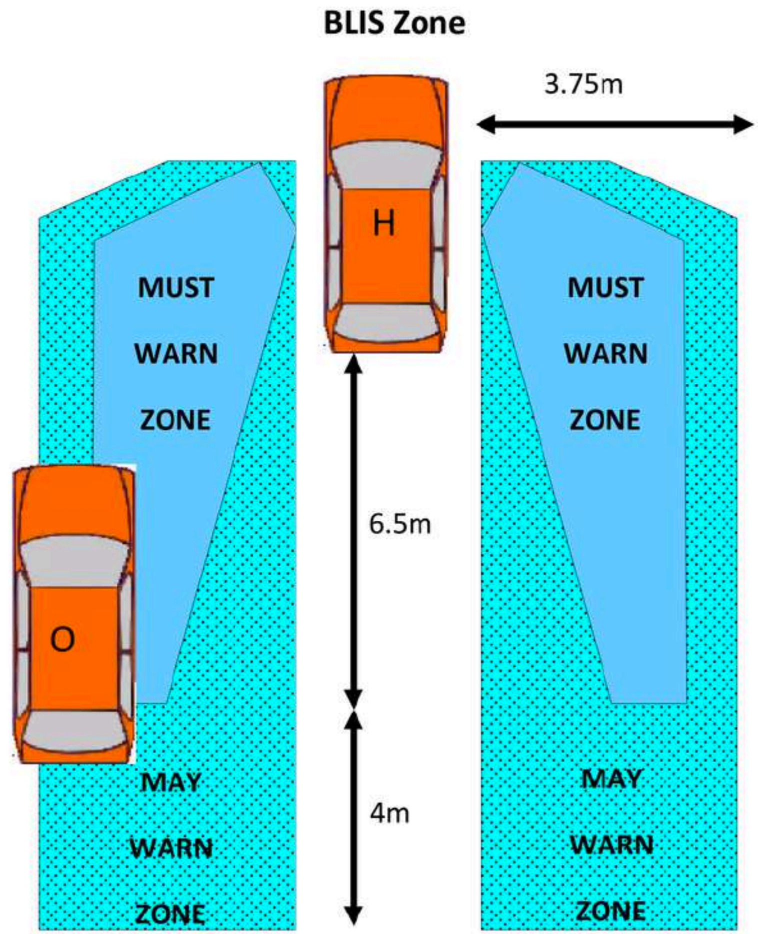


# Vehicle Sensors

- Delphi SRR2 Rear & Side Radar



# Vehicle Sensors

- ibeo "IBE-1000003-LUX+" LiDAR
  - Range up to 200m/650ft
  - Object tracking (up to 65 objects)

| LASER / OPTICAL | ibeo LUX 4L | ibeo LUX 8L | ibeo LUX HD |
|---|---|---|---|
| **Laser class:** | Class 1 | | |
| **Wave length:** | 905 nm | | |
| **Technology:** | Time of flight, Output of distance and echo pulse width | | |
| **Range:** | 50 m / 164 ft @ 10 % remission | 50 m / 164 ft @ 10 % remission | 30 m / 98 ft @ 10% remission |
| **Horizontal field of view:** | 110° (50° to -60°) | | |
| **Vertical field of view:** | 3.2° | 6.4° | 3.2° |
| **Multi-layer:** | 4 parallel scanning layers | 8 layers (2 pairs of 4 layers) | 4 parallel scanning layers |
| **Multi echo:** | Up to 3 distance measurements per shot (allow measurements through atmospheric clutter like rain and dust) | | |
| **Data update rate:** | 25.0 Hz | | |

# Vehicle Sensors

## • Mobileye "MBL-630-CAM-KIT+"

- EyeQ2® Image Processing SOC
- EyeWatch® display

- 2 seconds ahead warning:
  - Forward Collision
  - Pedestrian & Cyclist Collision

| Item | Description | Value |
|---|---|---|
| Signals Cables | Car inputs | BAT+, GND, Ignition, High Beam, CAN-Bus (High/Low) |
| Voltages | Input | 12 - 36VDC |
| | Current Load (full operation) | 12v > 360mA, 24v > 180mA** |
| | Stand-by Current Load (Ignition off) | 12v > 10µA, 24v > 10µA |
| | Power consumption | Nominal 5.2W |


- Forward Collision Warning
- Pedestrian and Cyclist Collision Warnings
- Lane Departure Warning
- Headway Monitoring and Warning
- Intelligent High-Beam Control *
- Speed Limit Indication

# Vehicle Sensors

- Allied Vision "AVT-MAKO-G-319C+" Camera

- Mono and Color modes
- Global Shutter
- Auto exposure
- Gamma correction

V.S. rolling shutter?

| | |
|---|---|
| Interface | IEEE 802.3 1000BASE-T, IEEE 802.3af (PoE) |
| Resolution | 2064 (H) × 1544 (V) |
| Sensor | Sony IMX265 |
| Sensor type | CMOS |
| Sensor Size | Type 1/1.8 |
| Cell size | 3.45 µm x 3.45 µm |
| Lens mount | C-Mount |
| Frame rate | 37.5 fps |
| ADC | 12 Bit |
| Image buffer (RAM) | 64 |

# Vehicle Sensors - Perception

- Velodyne "VEL-VLP-16+" LiDAR


- 16 Channels
- Measurement Range: 100 m
- Range Accuracy: Up to ±3 cm (Typical) 1
- Field of View (Vertical): +15.0° to -15.0° (30°)
- Angular Resolution (Vertical): 2.0°
- Field-of-View (Horizontal): 360°
- Angular Resolution (Horizontal/Azimuth): 0.1° – 0.4°
- Rotation Rate: 5 Hz – 20 Hz

- 3D LiDAR Data Points Generated:
- - Single Return Mode: ~300,000 points per second
- - Dual Return Mode: ~600,000 points per second

# Summary

- Signal
- Noise
- Time-domain Analysis
- Frequency-domain Analysis
- Signal processing filter design
- Electromagnetic spectrum
- Vehicle sensors (perception)

END, Thank you

# Reference


- Smith, Steven W. "The scientist and engineer's guide to digital signal processing." (1997): 35.
- Digital Signal Processing and Analysis, Lecture Notes, The University of Michigan, Jeffrey A. Fessler.
- Introduction to Electronics, Signals, and Measurement, Lecture Notes, Massachusetts Institute of Technology, Manos Chaniotakis and David Cory.

# Appendix Related Resource

- The Scientist and Engineer's Guide to DSP
- Vehicle Environment Sensing (Perception)
- Signals & Systems Series (Video)
- Fourier Transform - A visual introduction (Video)
- Signal Processing and Machine Learning Techniques for Sensor Data Analytics in Matlab (Video)
- Signal Processing - create A Digital Filter in Python (Video)
- Automotive Sensors (Video)