AuE 8200: 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

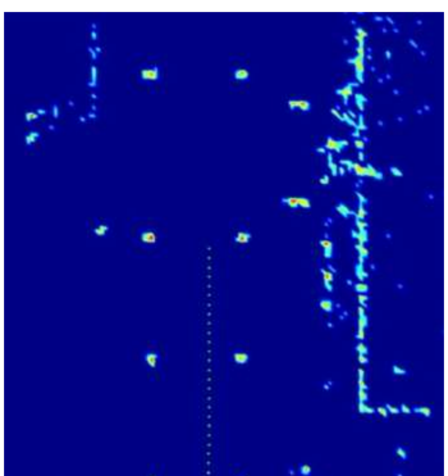
Time domain

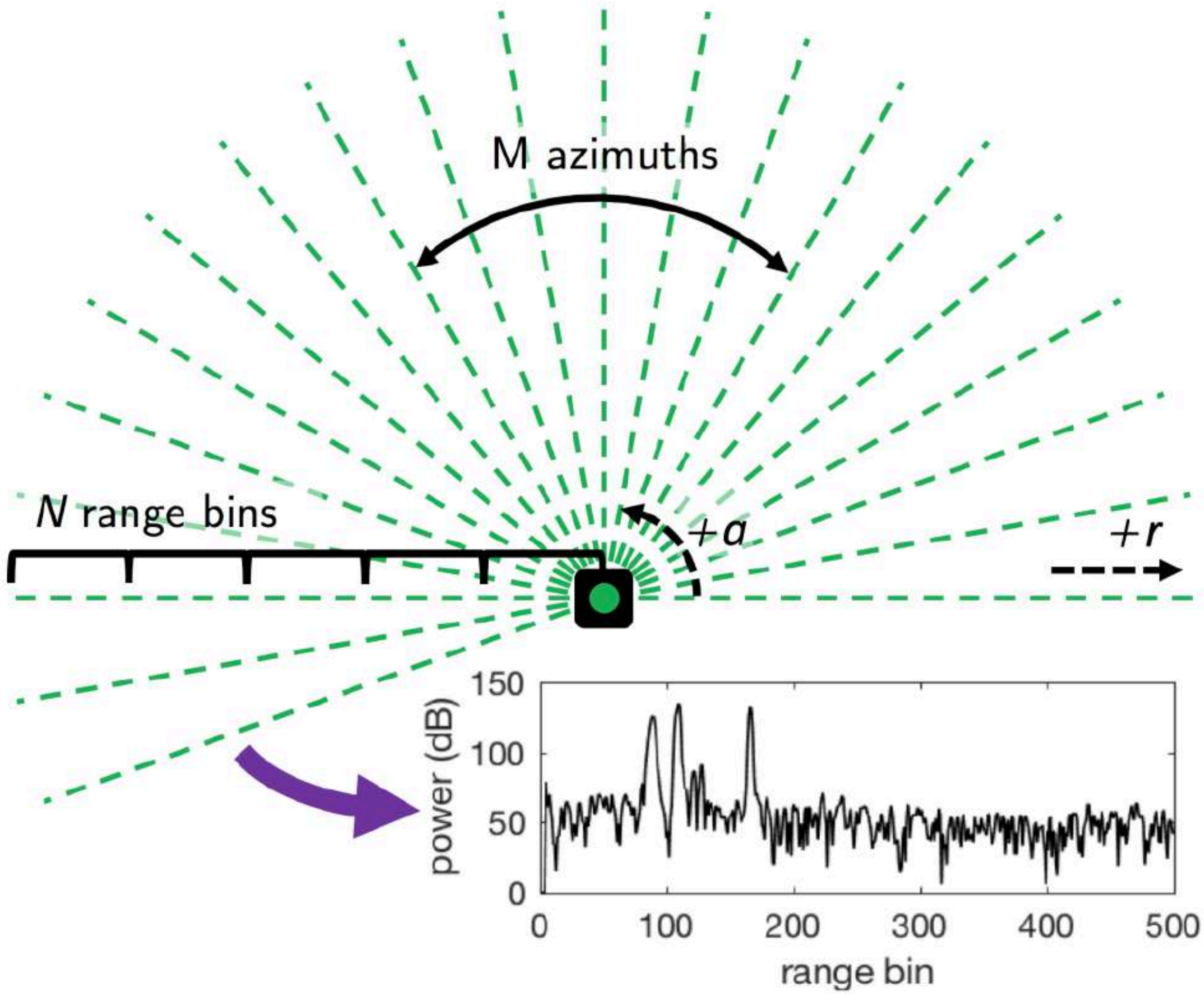
Frequency domain

Noise filter

Patterns

…





2D Signal: Image

Time domain

Frequency domain

Noise filter

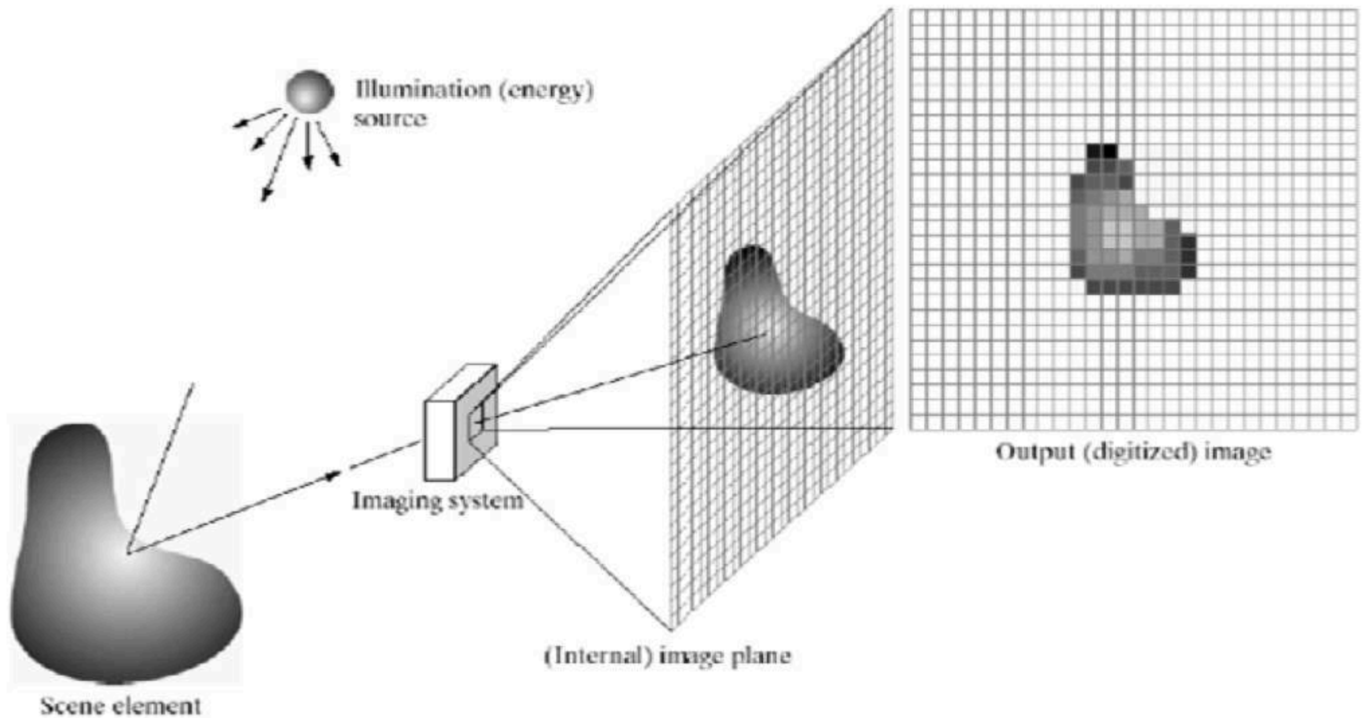
Multi-view

Features

Patterns

Understanding

…



3D Signal: Point Cloud

Time domain

Frequency domain

Noise filter

Geometry analysis, mapping

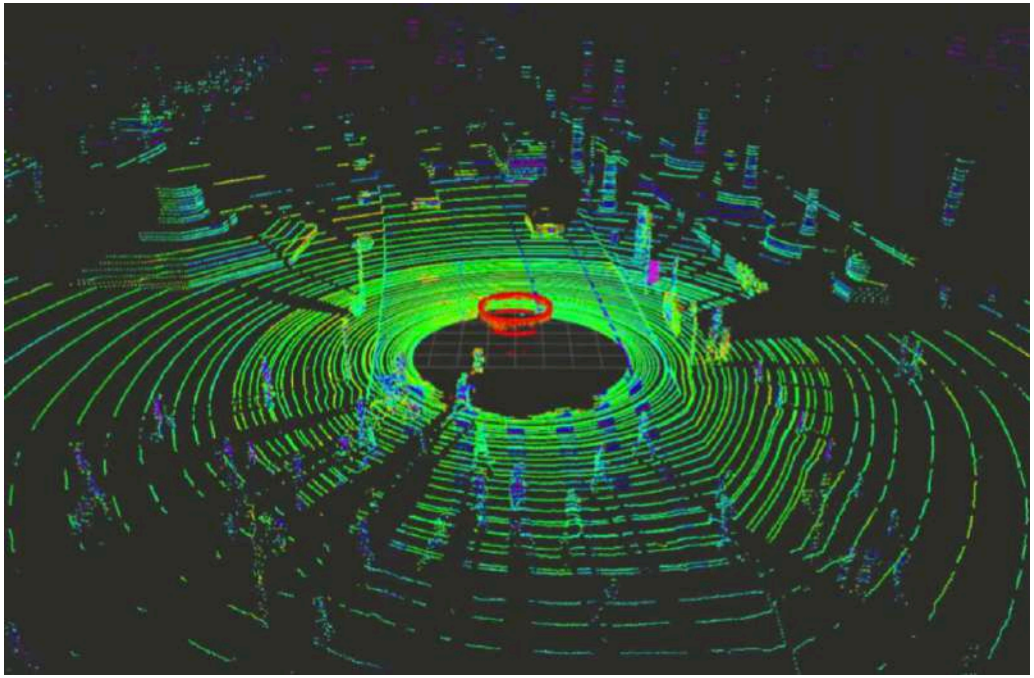
Features

Patterns

Understanding

…

Fuse with 2D vision

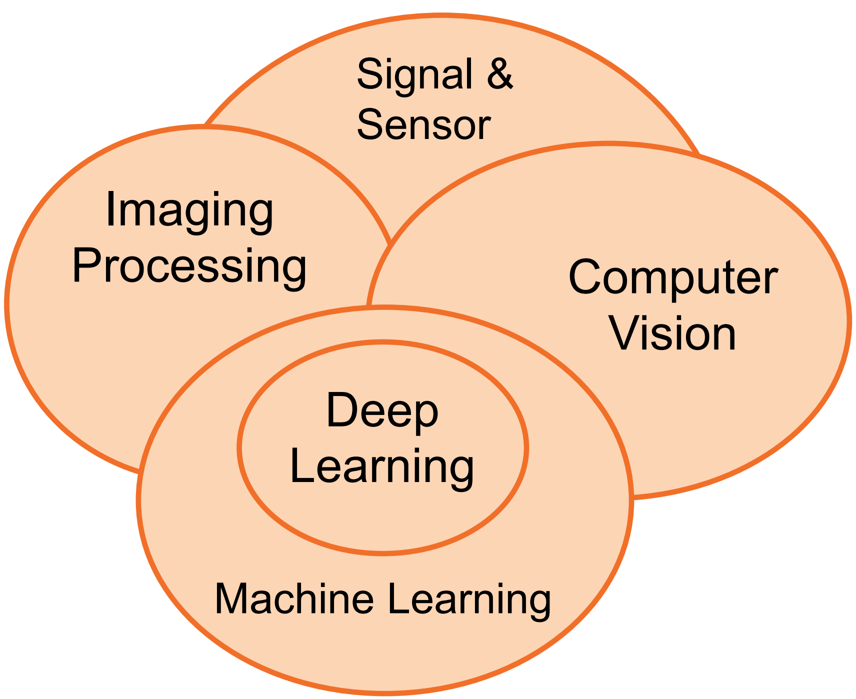


Signal and Sensor Data Analysis

- Applications

  Vehicle perception
  ADAS (Advanced driver-assistance systems)
  Autonomy

- Areas



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

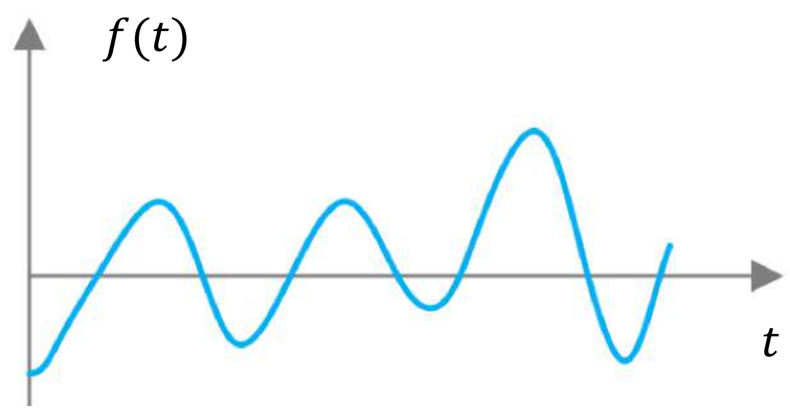
Signal and Sensor Perception

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

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

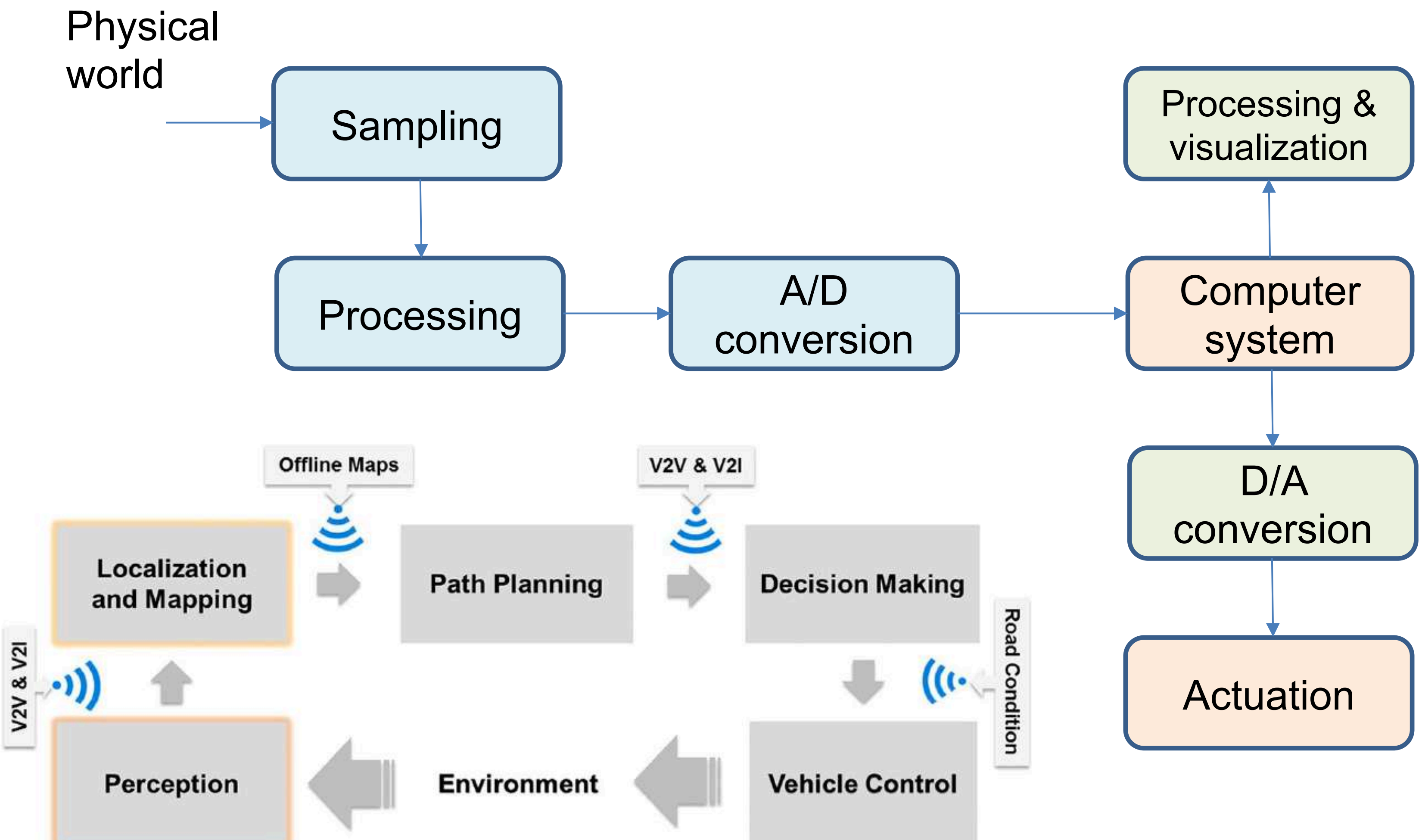
- Exteroceptive:
  Scene, geometry, object, …

- Analog signal
  Continuity in
  - Time domain
  - Amplitude



Signal and Sensor Perception

- Sensor perception → vehicle actuator control

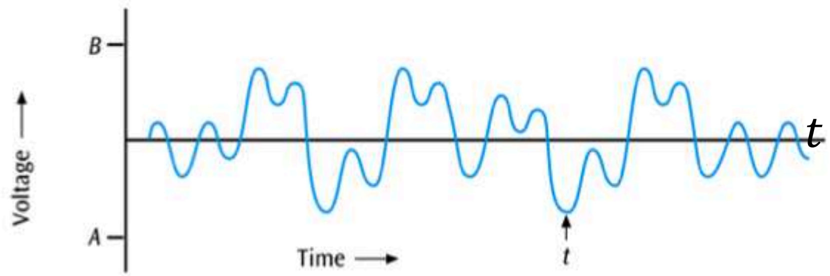


Signal and Sensor Perception

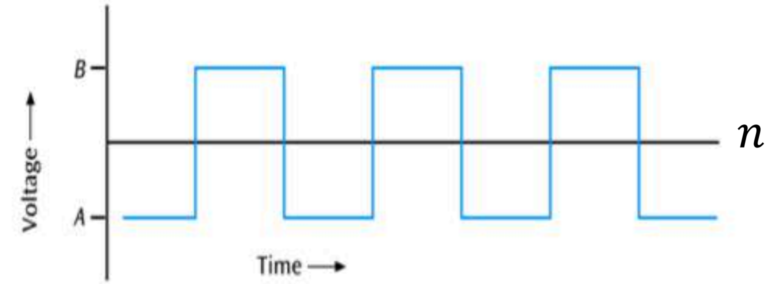
- Analog signal VS. Digital signal

A/D (Analog-to-Digital)

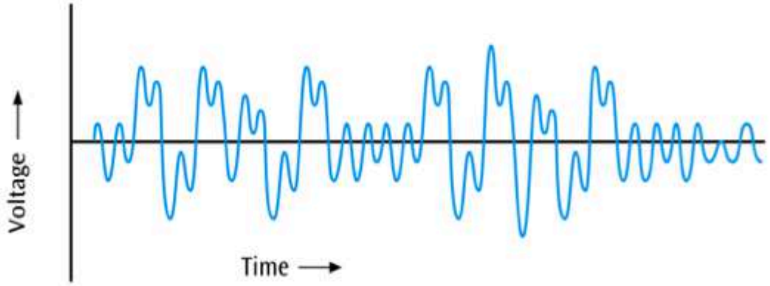
$f(t)$

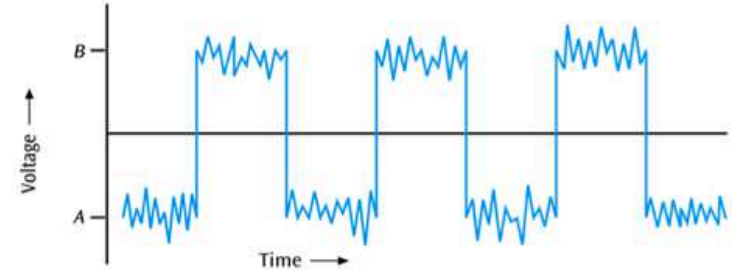


$f(n)$



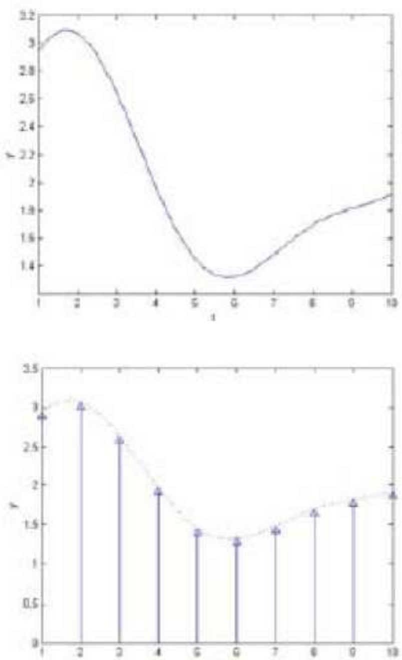
Affected by noise or EMI (Electromagnetic interference)



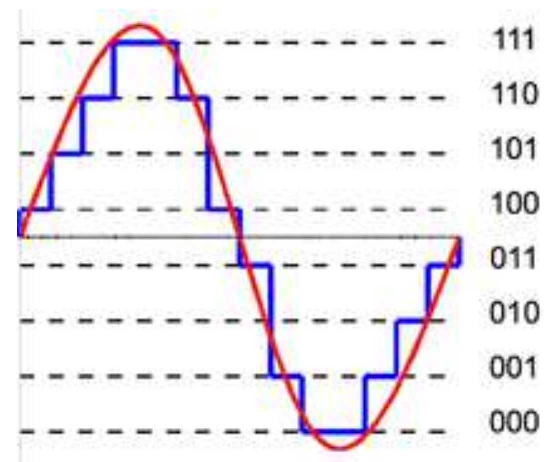


Signal A/D (Analog-to-Digital)

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



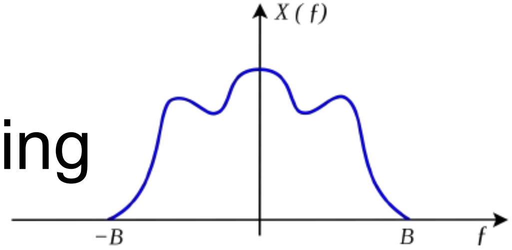
Uniform quantization



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 (μ_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 (σ^2) and standard deviation (σ) of a signal

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

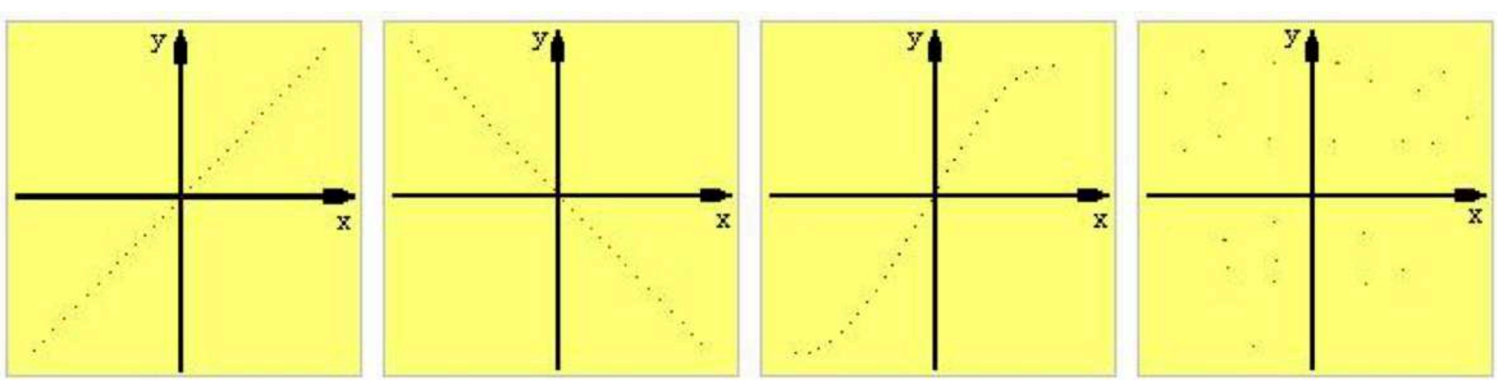
Time Domain Analysis

- Covariance

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

- Statistical correlation

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



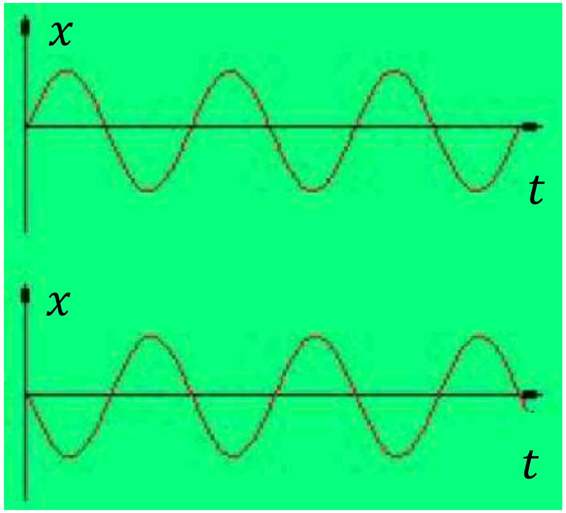
$\rho_{xy} = 1$ $\rho_{xy} = -1$ $0 \leq \rho_{xy} \leq 1$ $\rho_{xy} = 0$ Relationship?

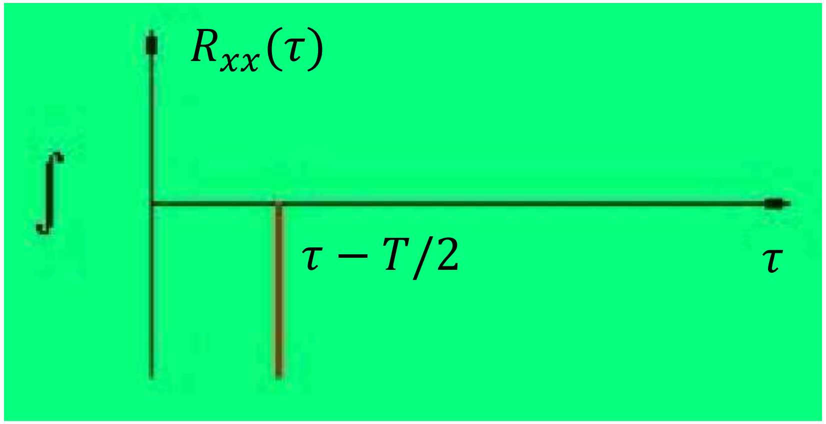
Time Domain Analysis

- Correlation function for continuous signals

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

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



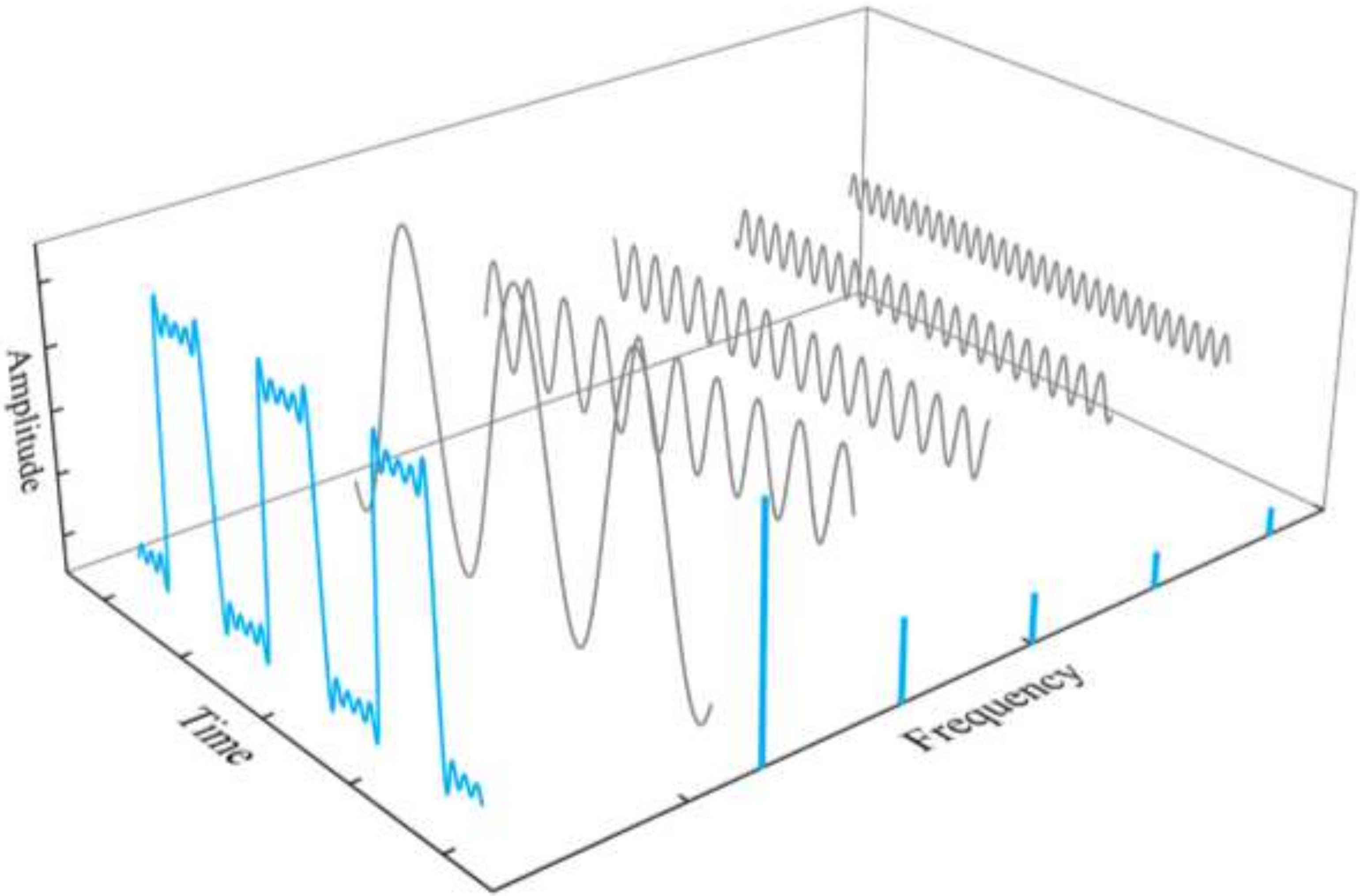


Similarity between two signals, or one signal with time shift

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 ($\otimes$): $\mathrm{y[k]} = \sum_{n=-\infty}^{\infty} x_1[n] x_2[n - k]$
  - 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



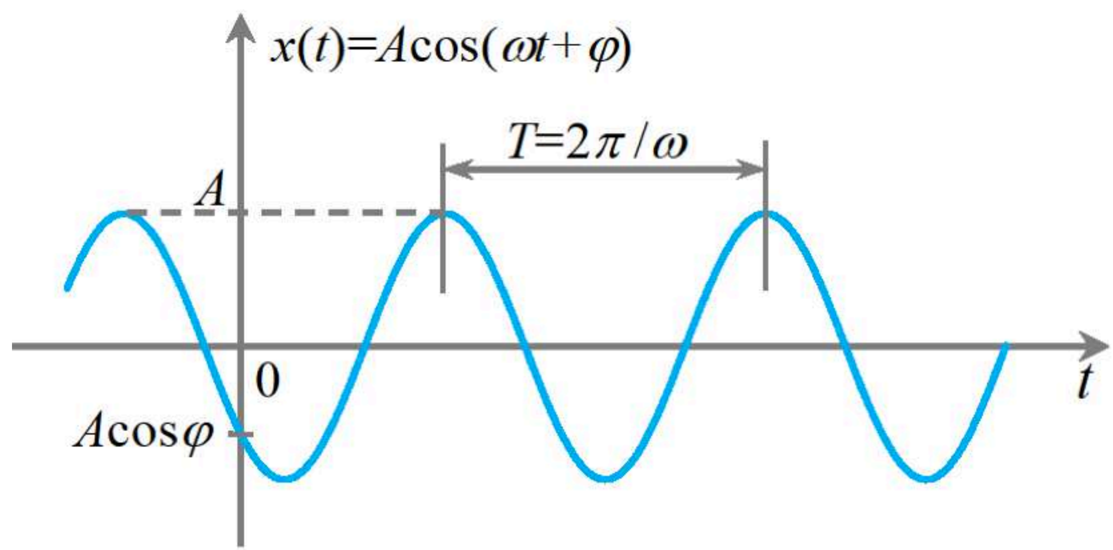
Signal Frequency Analysis

- Frequency domain

- A typical signal: *sin* wave

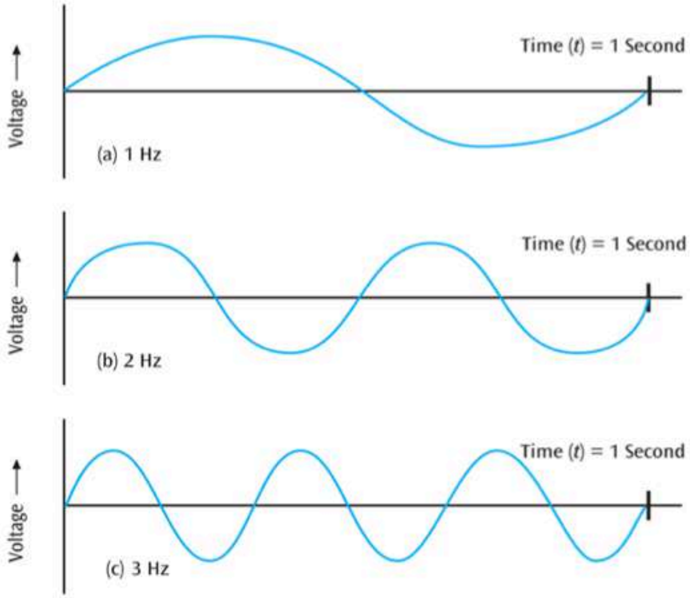
$$x(t) = A\cos(\omega t + \varphi)$$

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



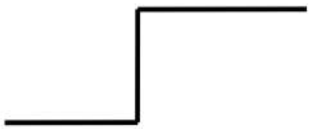
Signal Frequency Analysis

- 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:

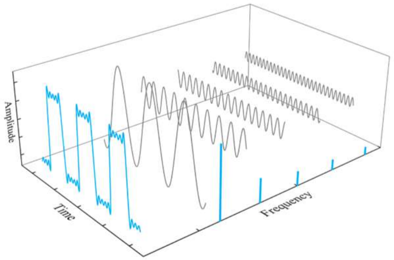
$$X_k = \frac{1}{T} \int_0^T x(t)\, e^{-jk\omega_0 t}\, dt$$

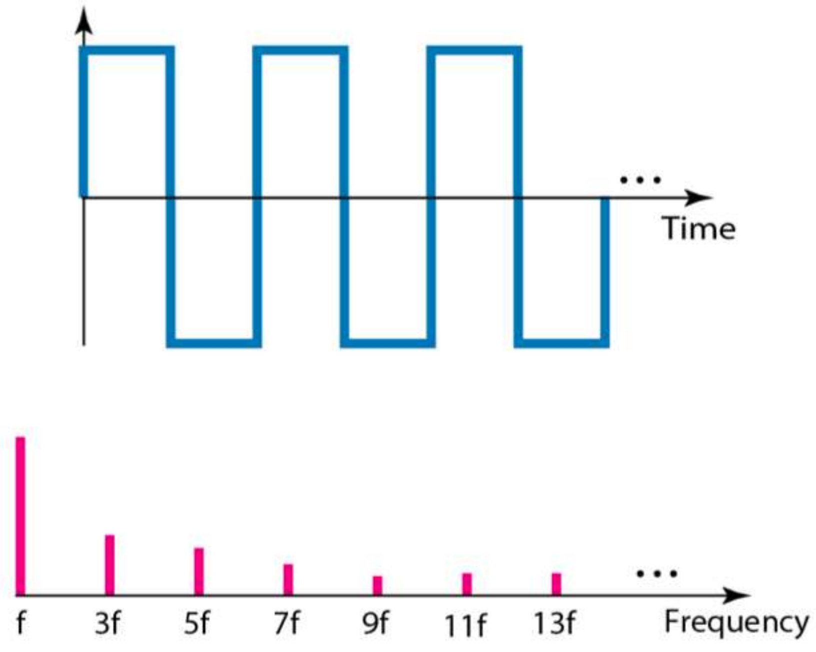
- For each frequency components:
  Frequencies $k\omega_0$; Amplitude $|X_k|$; Phase $arctan \frac{Im(X_k)}{Re(X_k)}$, atan2

Signal Frequency Analysis

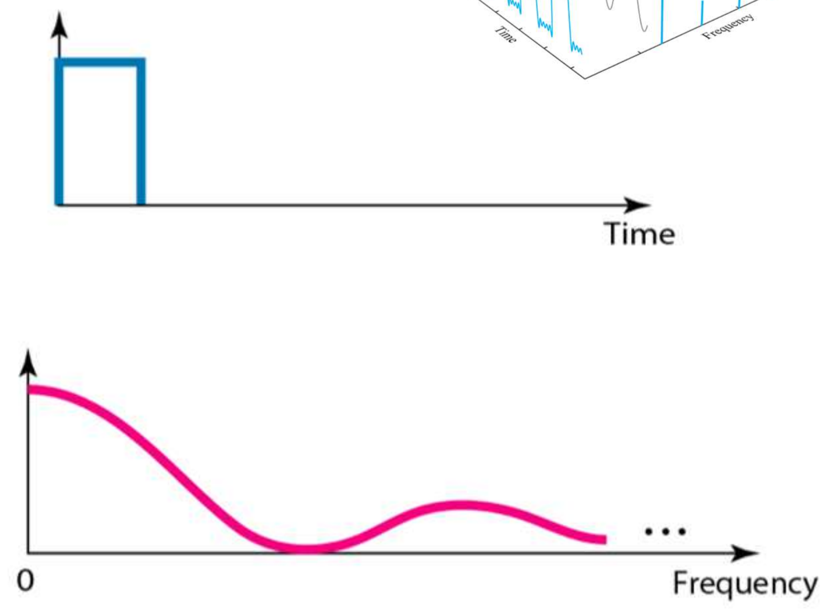
- DFT difference for periodic and aperiodic signal in Trigonometric series

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





First/Second/… **harmonic** components

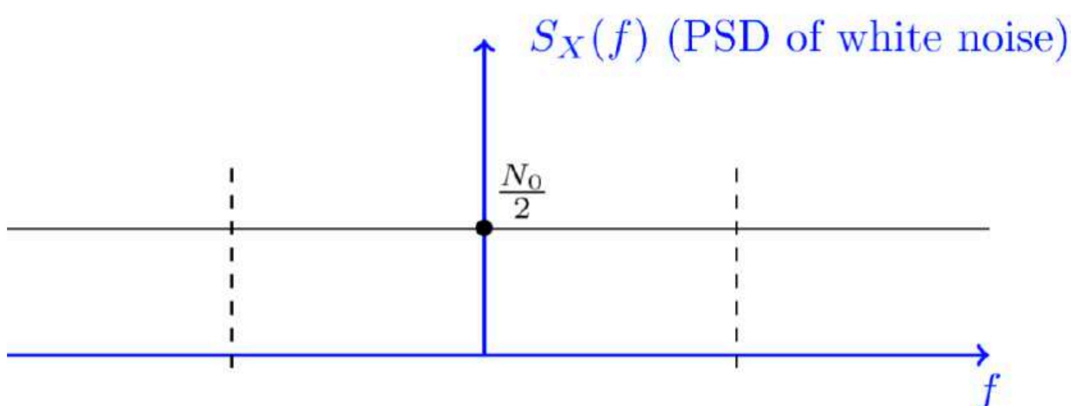


Signal Noise

- Fourier transformation: *F*
  - Time, Frequency

- Power Spectral
  - *F* (y[k]), where Auto-correlation $y[k] = \sum_{n=-\infty}^{\infty} x[n]x[n-k]$
  - Power Spectral Density (PSD): $|X(f)|^2$, X is the *F* of x(k)

- White noise
  refers to "uniform power across the frequency".



[1]

Frequency range of interest

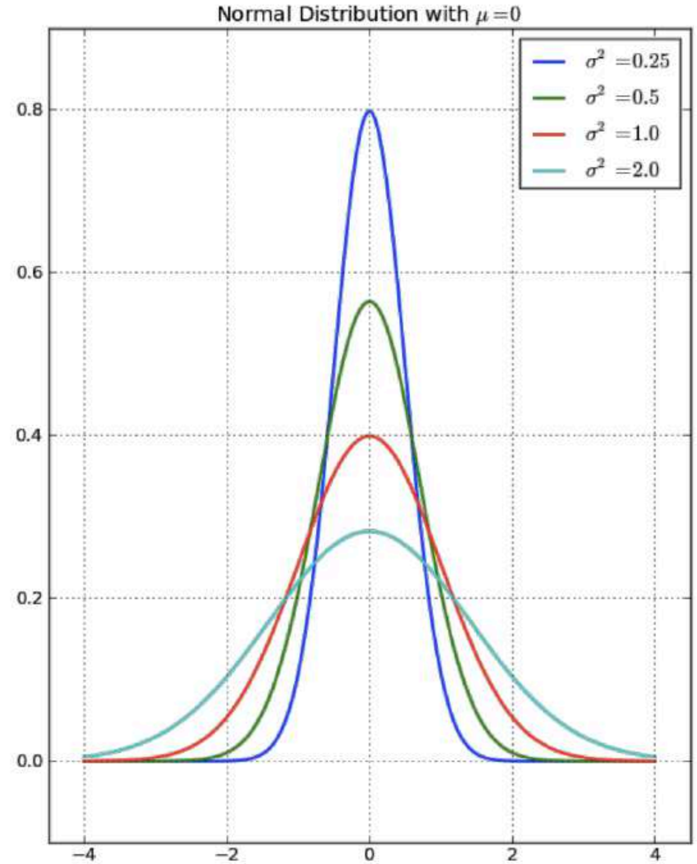
Signal Noise

- Gaussian noise
  refers to "normal distribution in the frequency domain"

A Gaussian random variable W with mean μ and variance σ^2 has a PDF described by

$$f_W(w) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(w-\mu)^2}{2\sigma^2}}$$

Aptitude
in FT domain



[1]

- White Gaussian noise
  (random sampling from Gaussian process)
  - Good approximation of many real-world situations;
  - Mathematically tractable models [2];

Signal Noise

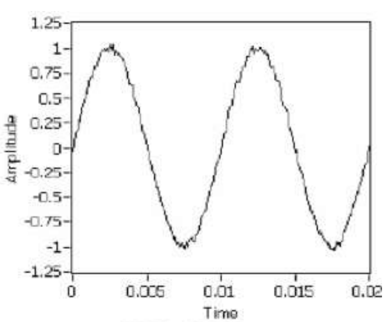
- Signal-to-noise ratio (SNR)

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

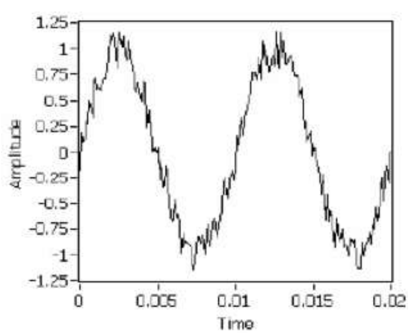
- Logarithmic decibel (dB) scale

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

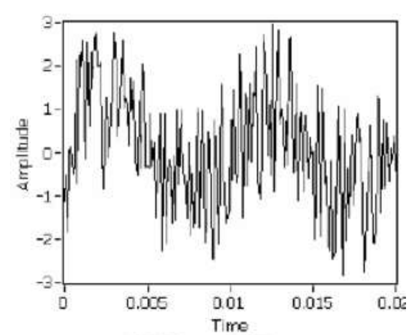
$$SNR_{dB} = 10 \log_{10} \frac{P_{signal}}{P_{noise}} = 20 \log_{10} \frac{A_{RMS,s}}{A_{RMS,n}}$$



SNR=26dB



SNR=14dB



SNR = -6dB

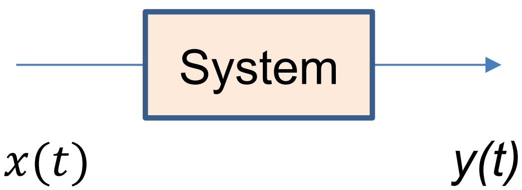
Signal Noise

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

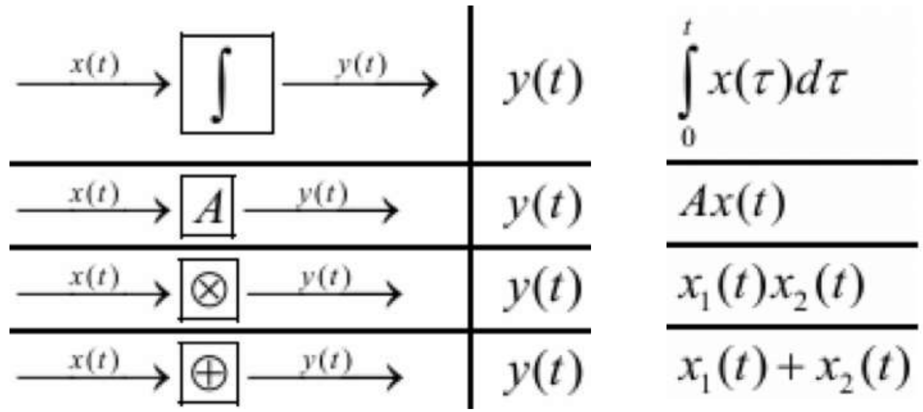
- Noise
  - A general term for all unwanted (probably immeasurable) modifications during signal capturing to processing process.
  - Wrong measurement doesn’t belong to noise.
- Noise types
  - Additive noise (White noise, Gaussian noise, Cauchy noise ...)
  - Multiplicative noise (multiplies or modulates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

Digital Signal Processing Systems

- From signal to systems



examples



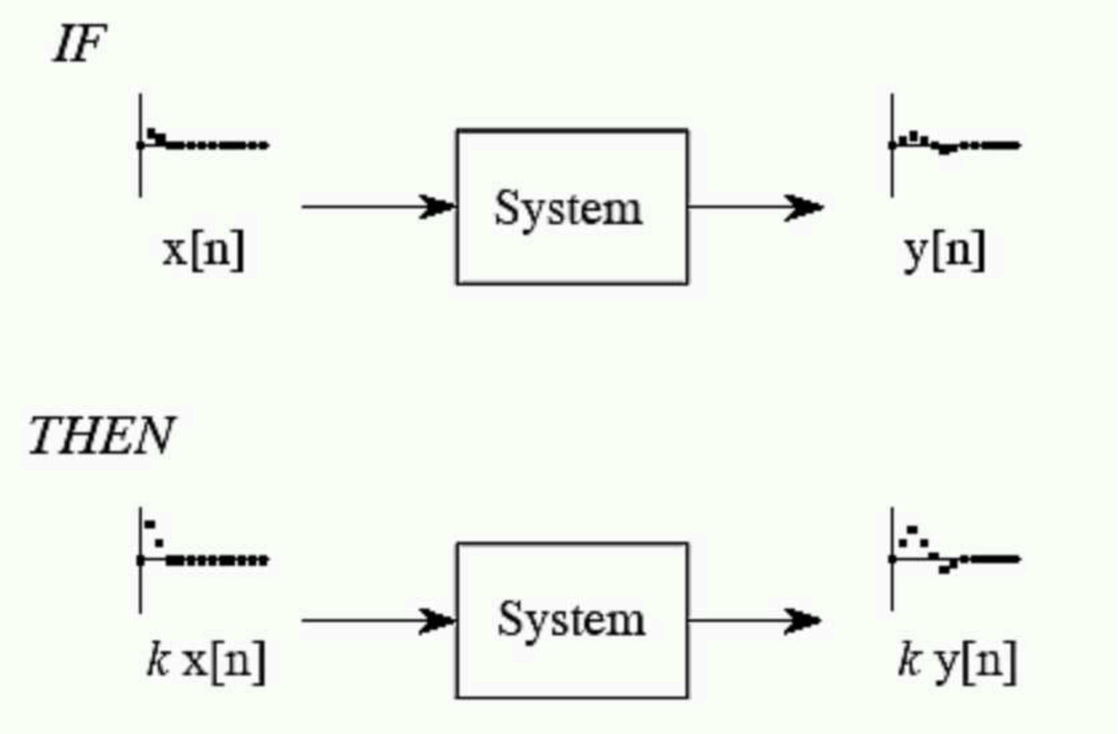
- Linear VS. Non-linear systems

- Characteristics of linear system
  - Homogeneity
  - Additivity

- Linear Time-invariant (LTI):
  $y(t)$ *for* $x(t)$ → $y(t-T)$ *for* $x(t-T)$

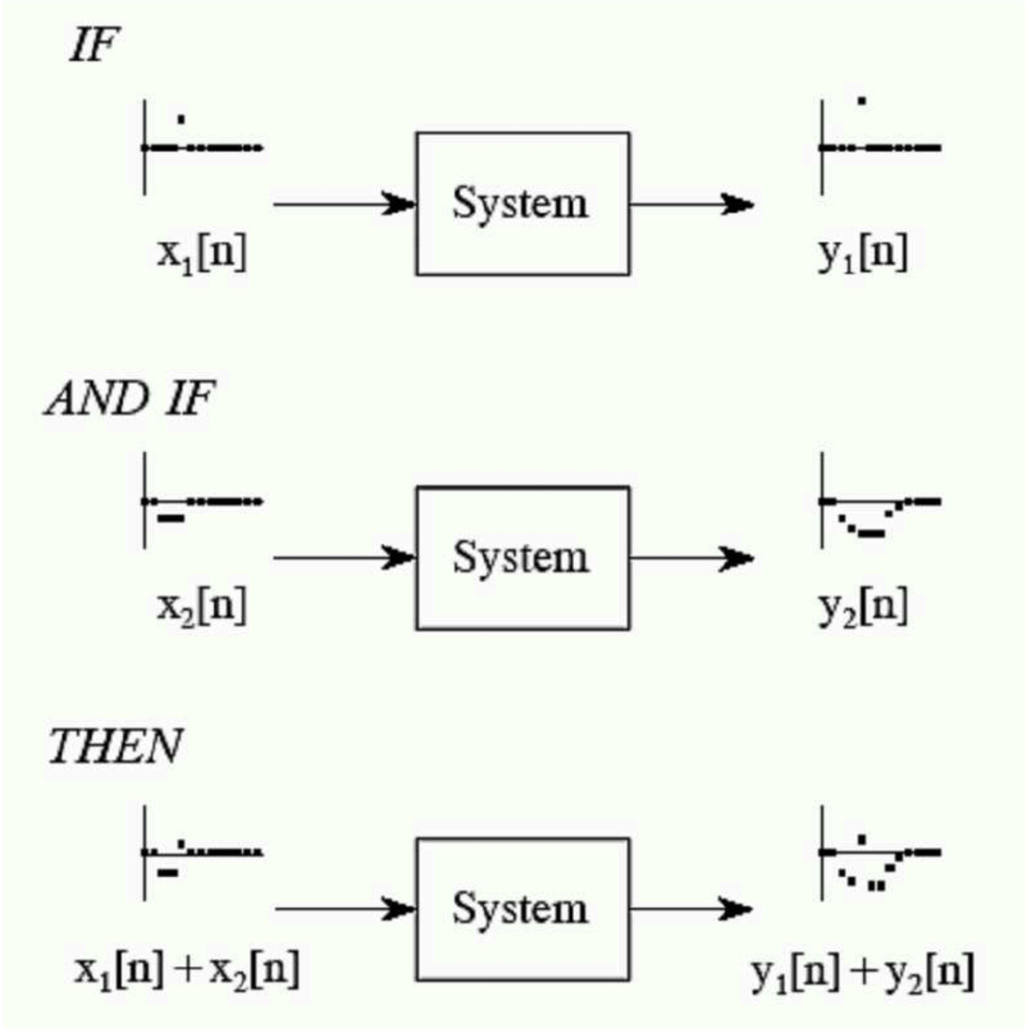
Digital Signal Processing Systems

- Homogeneity of linear systems



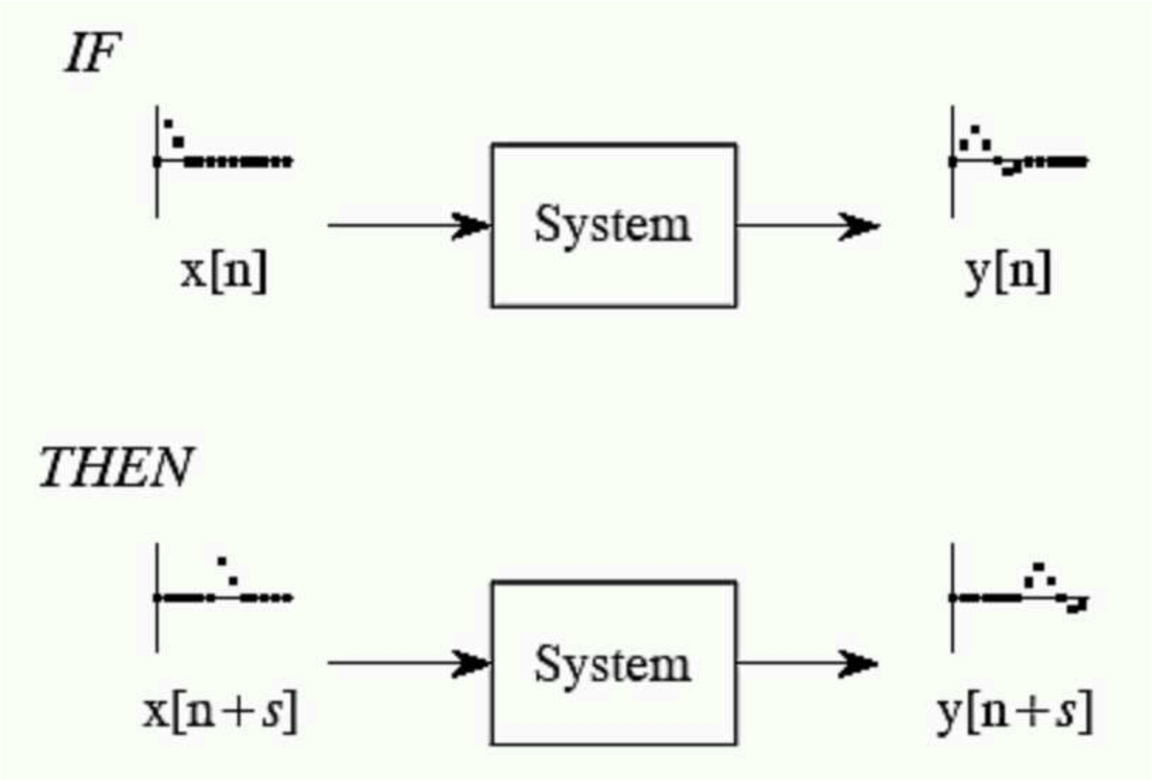
Digital Signal Processing Systems

- Additivity of linear systems



Digital Signal Processing Systems

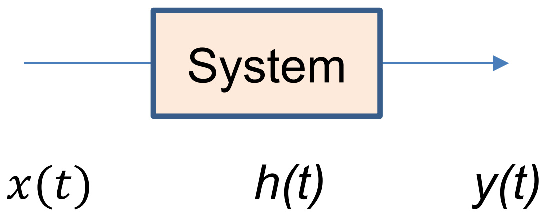
- Time-invariant systems



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

Digital Signal Processing Systems

- System analysis

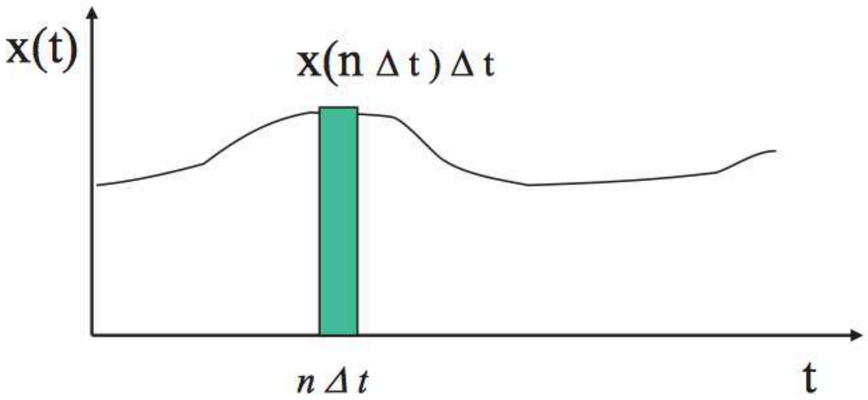


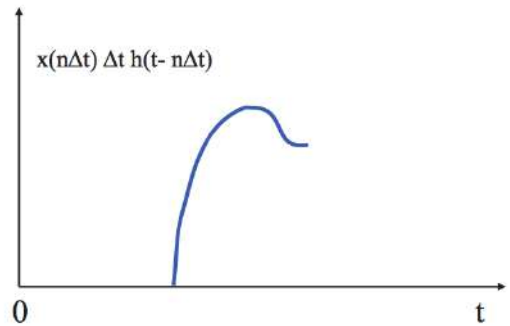
$h(t)$?

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

Digital Signal Processing Systems

- System response

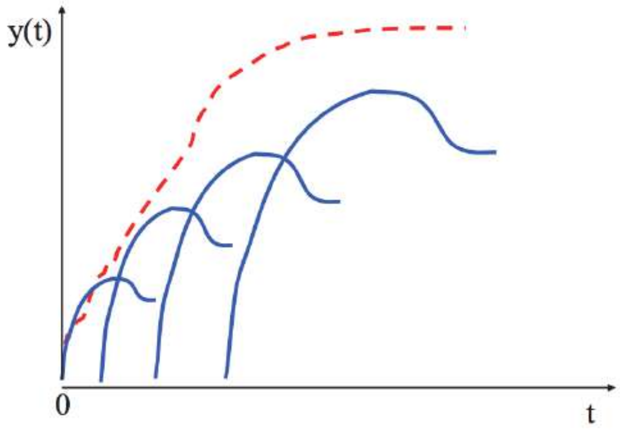




Response:

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

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



Signal convolution:

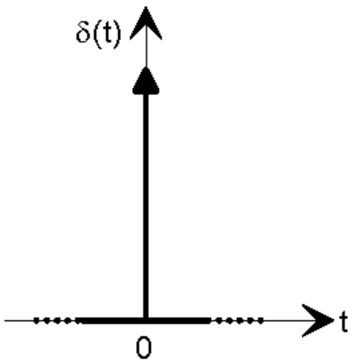
$$y(t)=x(t)*h(t)$$
$$=\int_{-\infty}^{\infty} x(\tau)h(t-\tau)d\tau$$

Digital Signal Processing Systems

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

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

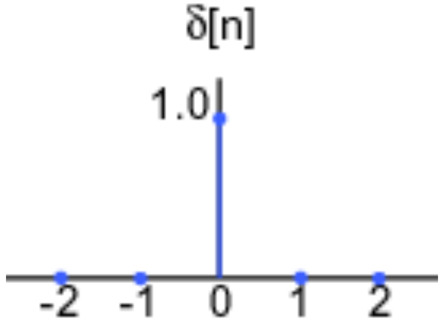
$$\lim_{\varepsilon\to 0}\int_{\tau_0-\varepsilon}^{\tau_0+\varepsilon}\delta(t-\tau_0)dt=1$$



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

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

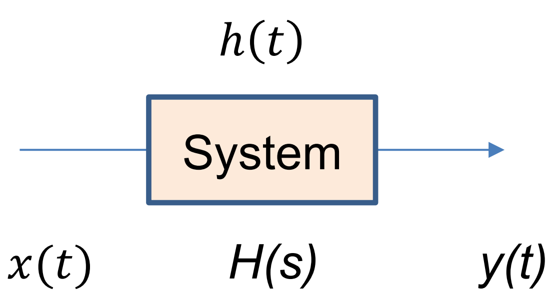
Digital Signal Processing Systems

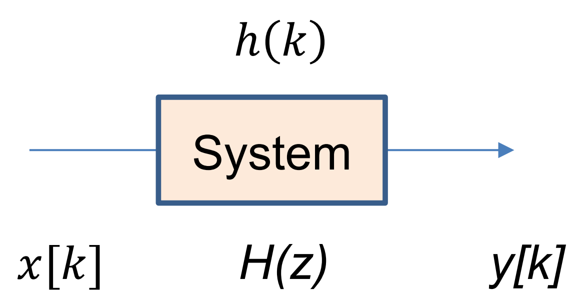
- All three transforms convert time-domain convolutions to polynomial equations

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

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

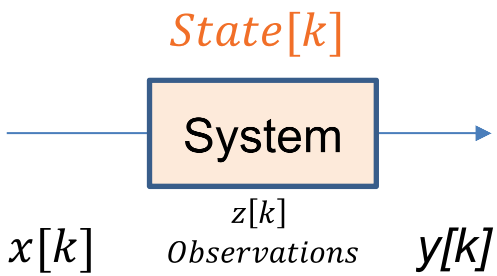
- Why Laplace transform and z transform?
  - Complex frequency-domain for Stability and Causality analysis





Digital Filter Design

- State-space filter



Using dynamic model
e.g.: Kalman filter

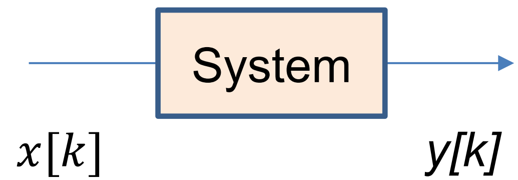
$$\bar{\mu}_t = A_t \mu_{t-1} + B_t u_t$$
$$\bar{\Sigma}_t = A_t \Sigma_{t-1} A_t^T + R_t$$

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

- Conventional digital filters

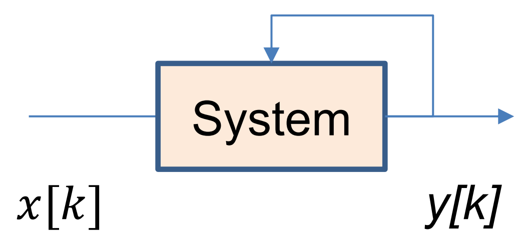
Finite Impulse Response (FIR) filters:

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



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

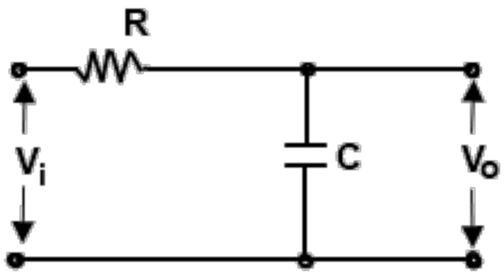
Design approaches:

Frequency sampling design
Fourier transform design

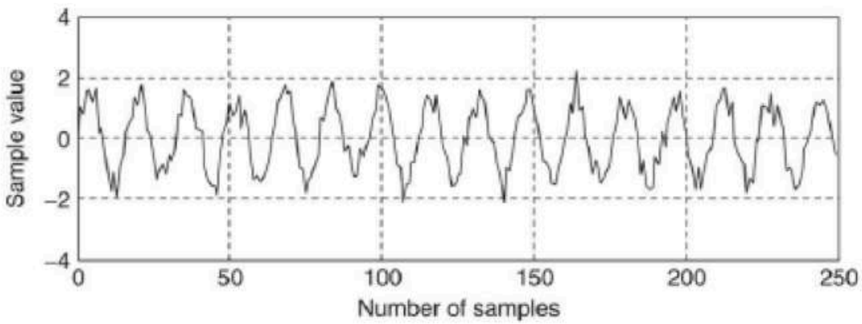
Bilinear transformation
Pole zero placement

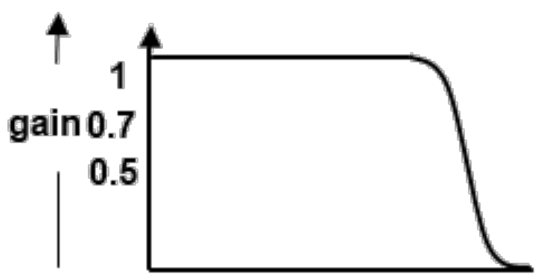
Digital Filter Design

- Example: low pass filter design

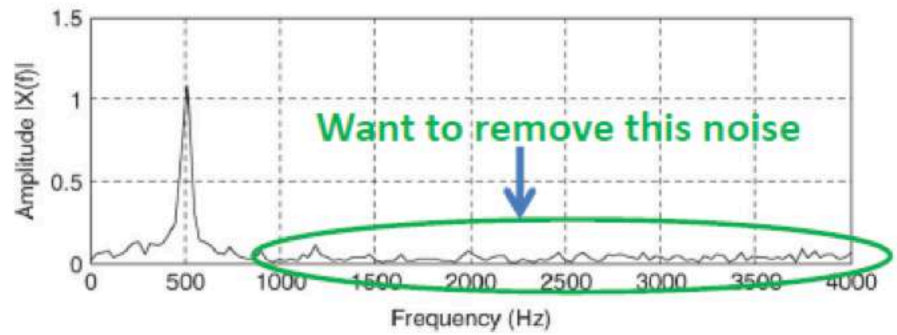


(a)RC low Pass Filter Circuit





(b) Frequency ResponseCurve



Digital Filter Design

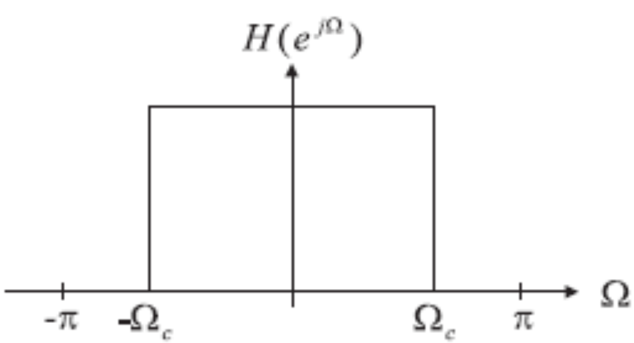
- 1st example: A simple average digital filter:

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

- 2nd example: (ideal) FIR low pass filter (LPF) design [1]

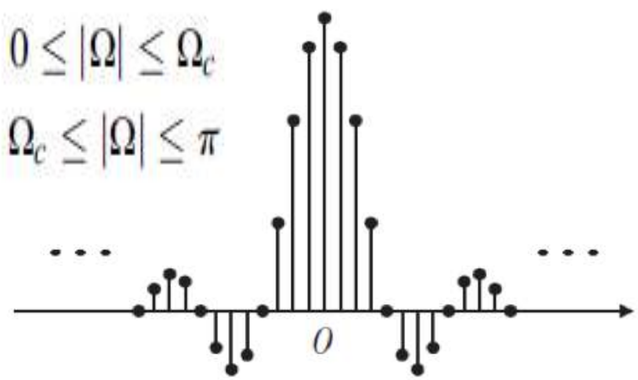
$$y[k] = \sum_{n=0}^{N} b_n x[k-n]$$

b_n: filter coefficients (aka: kernel)



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

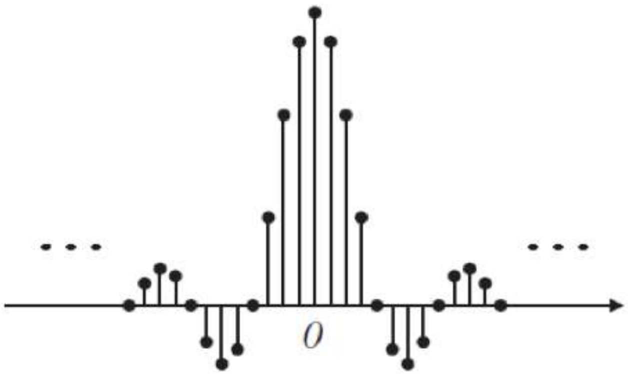
Inverse FFT



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 $\Rightarrow$

$$b_n = h(n - M)$$

for $n = 0, 1, \ldots, 2M$.

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

FIR low pass filter: transfer function

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

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

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:

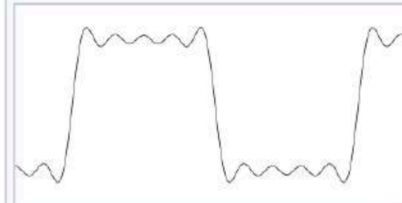
$$w_{tri}(n) = 1 - \frac{|n|}{M}, \; -M \leq n \leq M$$

3. Hanning window:

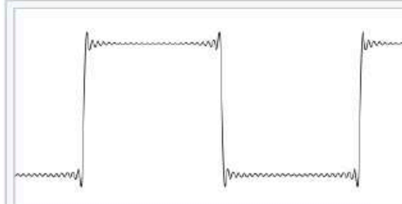
$$w_{han}(n) = 0.5 + 0.5 \cos\left(\frac{n\pi}{M}\right), -M \leq n \leq M$$

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

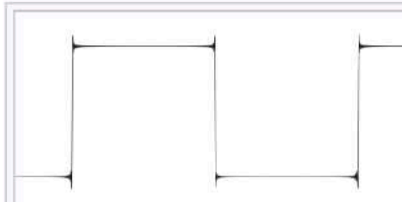
$$h_w(n) = h(n) \cdot w(n)$$



Functional approximation of square wave using 5 harmonics



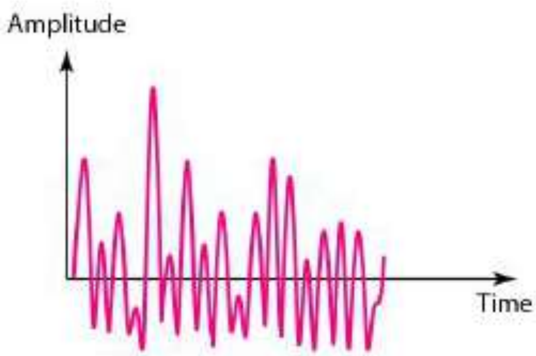
Functional approximation of square wave using 25 harmonics

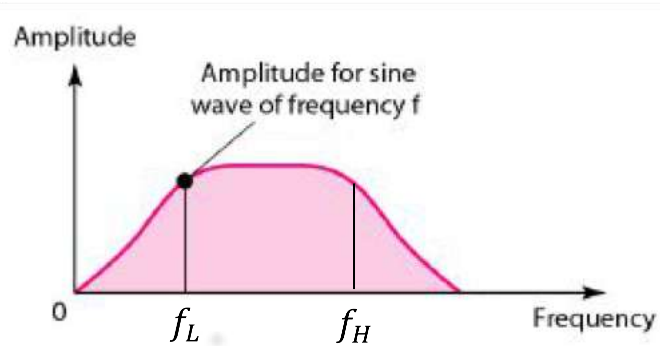


Functional approximation of square wave using 125 harmonics

Spectrum in Frequency Domain

- Frequency spectrum to bandwidth

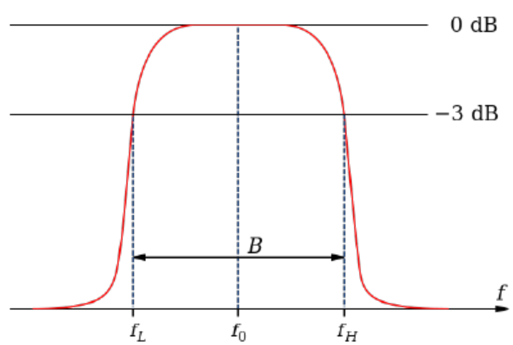


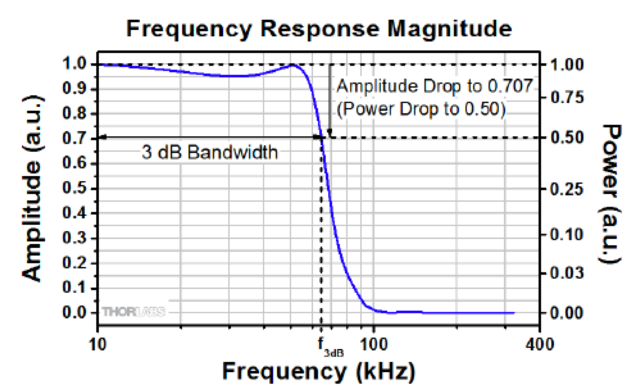


Bandwidth

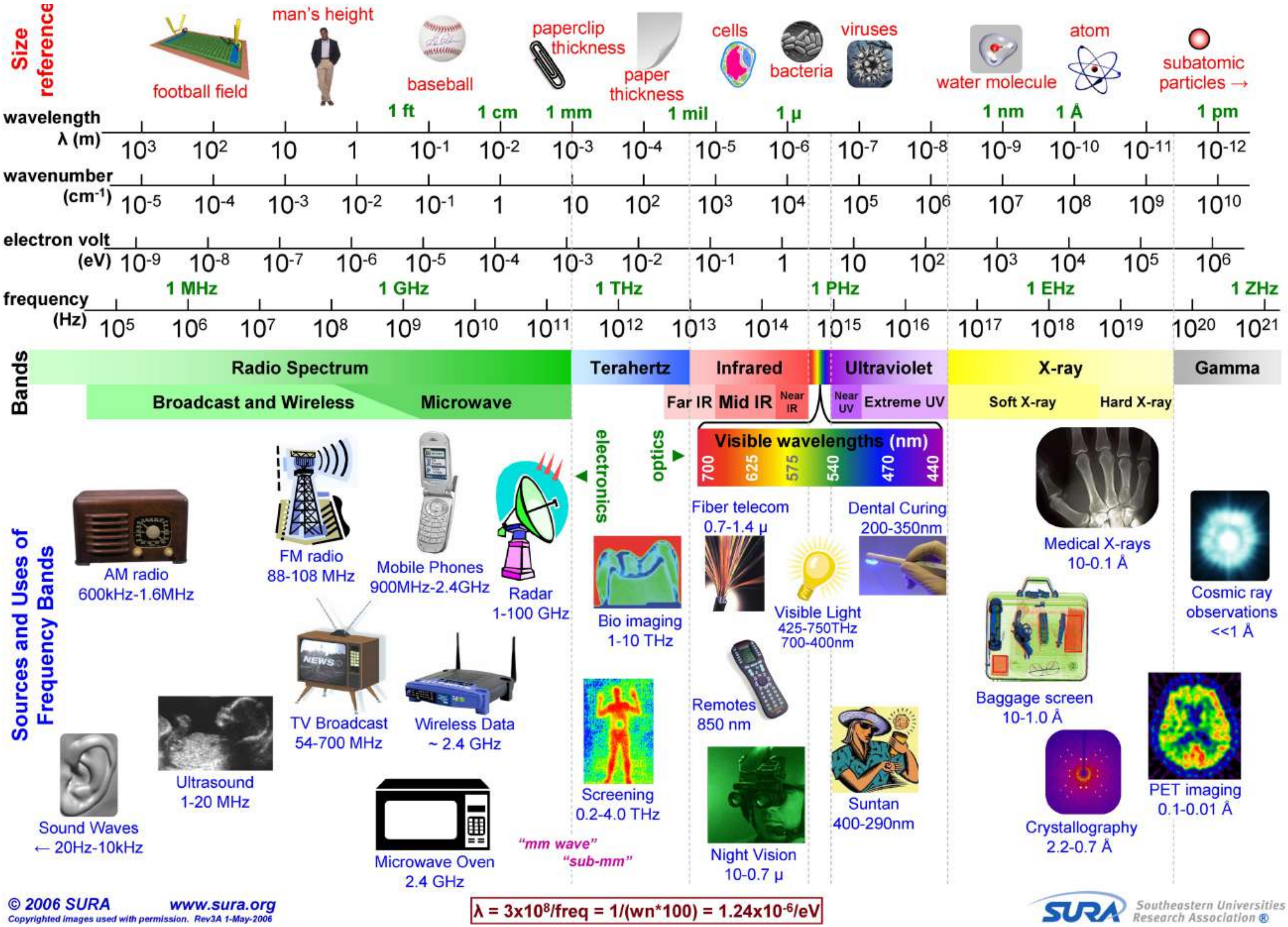
Effective bandwidth

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

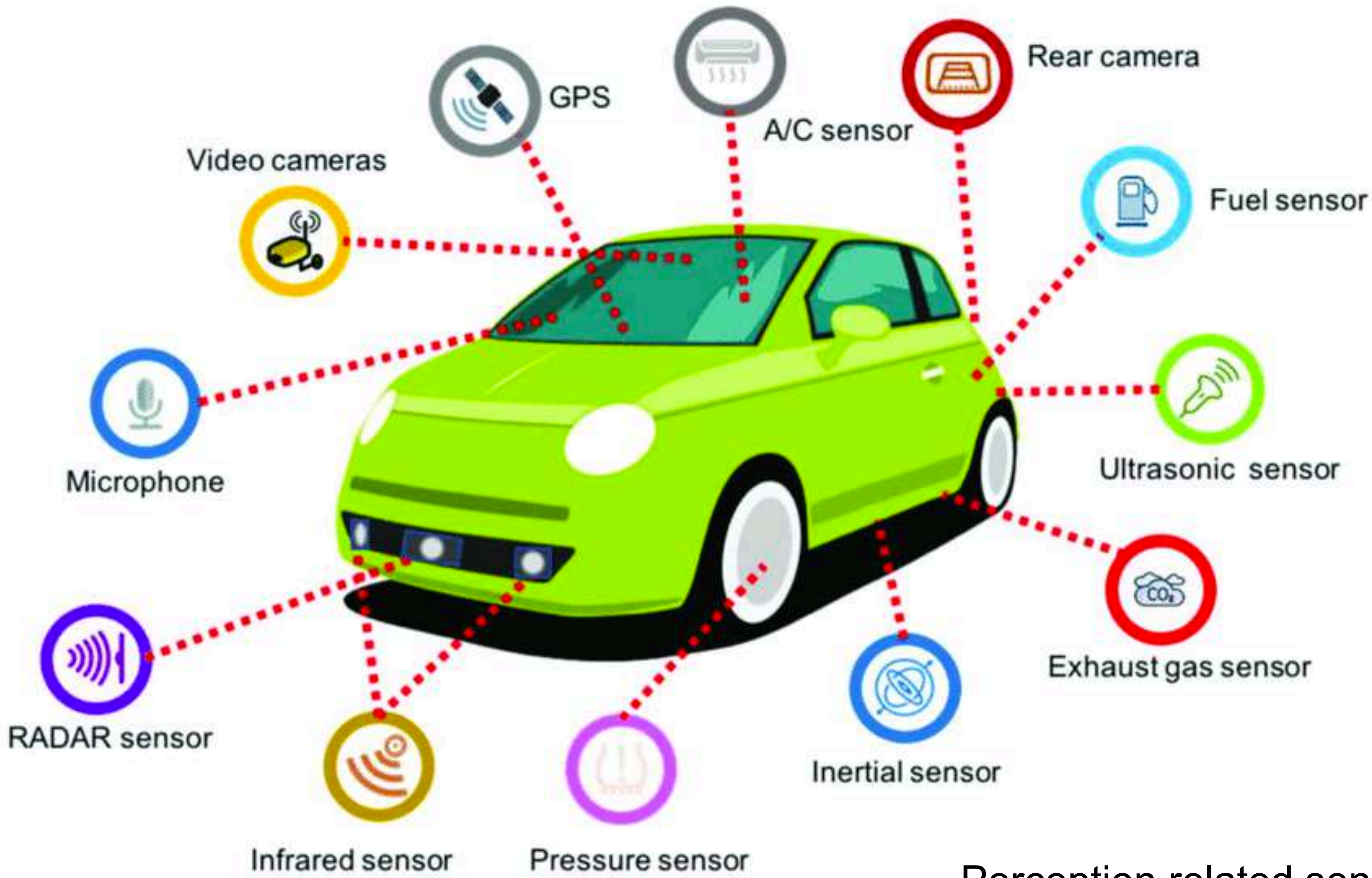




Electromagnetic Spectrum



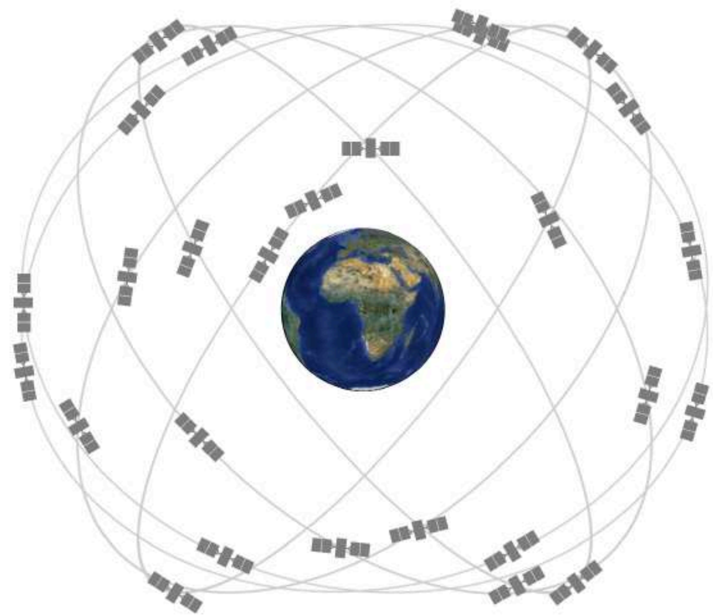
Vehicle Sensors



Perception related sensors

Vehicle Sensors

- GPS (Global Positioning System)
- A constellation of 24 satellites (+several spares)
- Broadcast time;
  identity;
  orbital parameters (latitude, longitude, altitude);
- Carriers - there are two carrier radio waves:
  - L1, with frequency 1575.42 MHz
  - L2, with frequency 1227.6 MHz

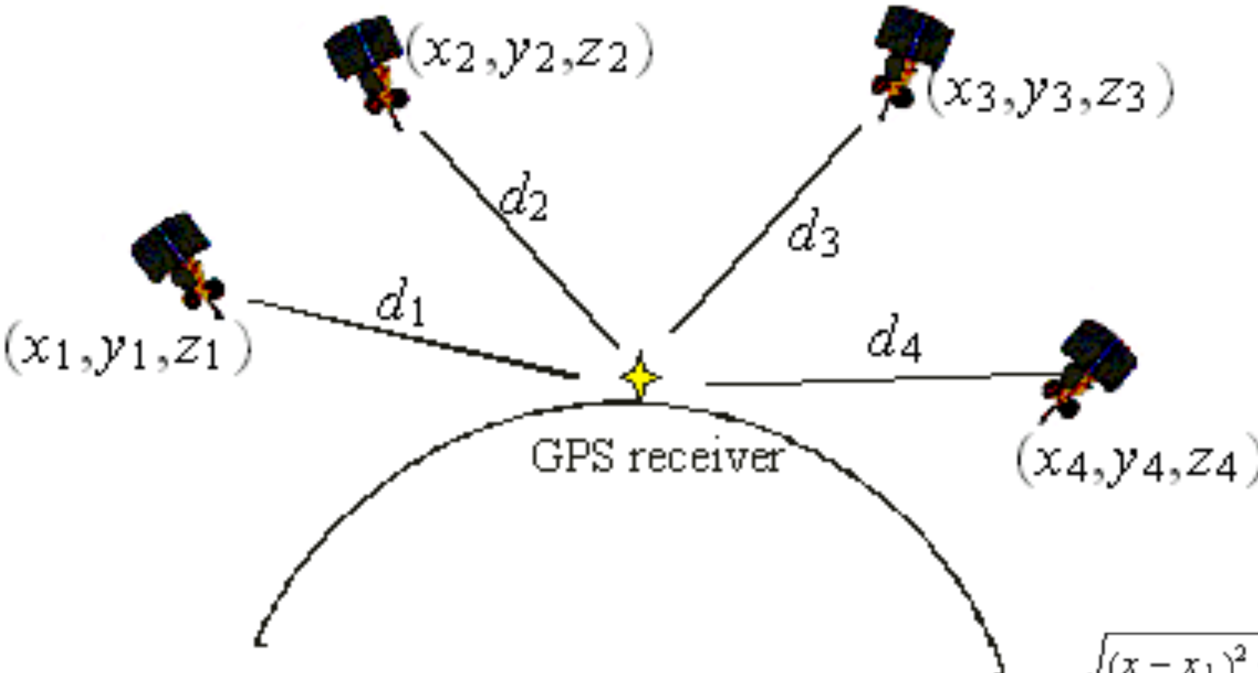


Space Segment

https://www.gps.gov

Vehicle Sensors

- GPS (Global Positioning System)



Triangulation

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

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

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

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

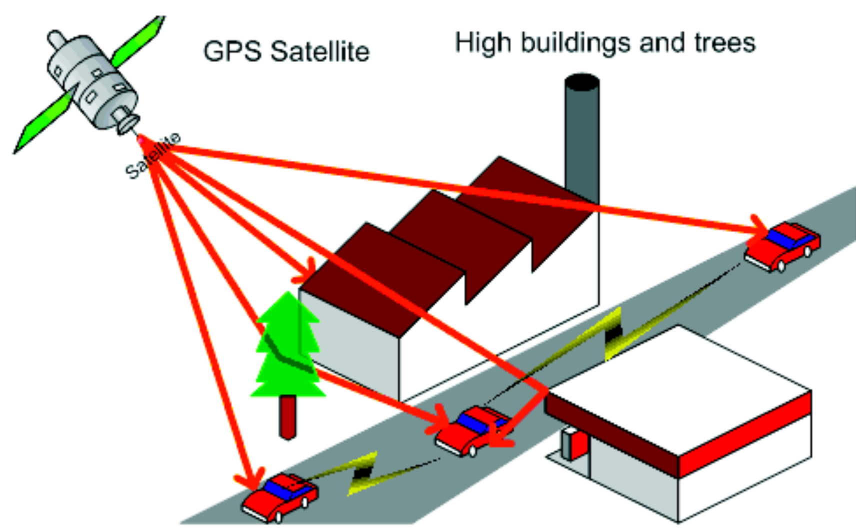
Vehicle Sensors

- 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

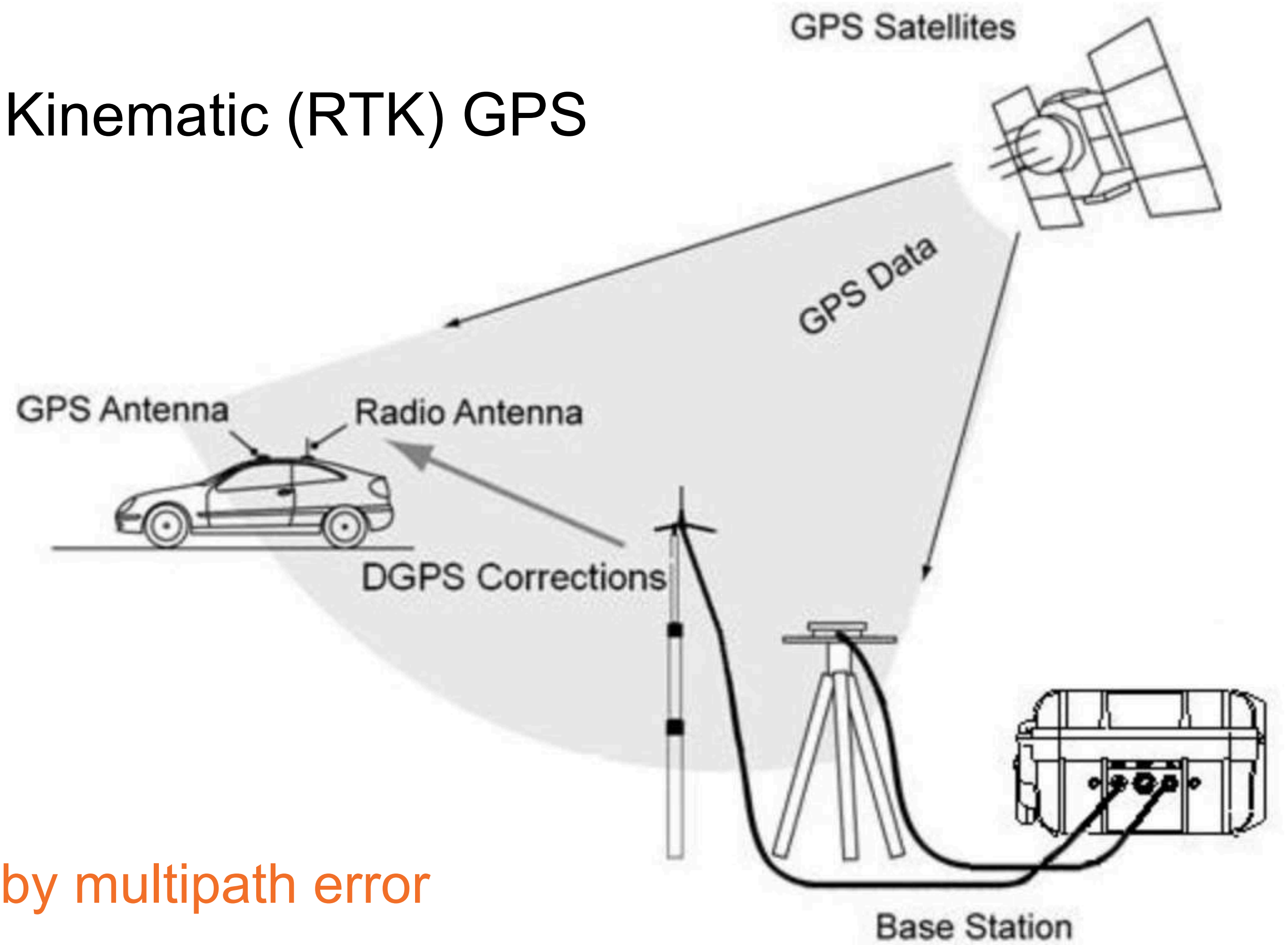
- PPS - Precise Positioning Service
  - uses multiple signals
  - for military use only



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

Vehicle Sensors

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



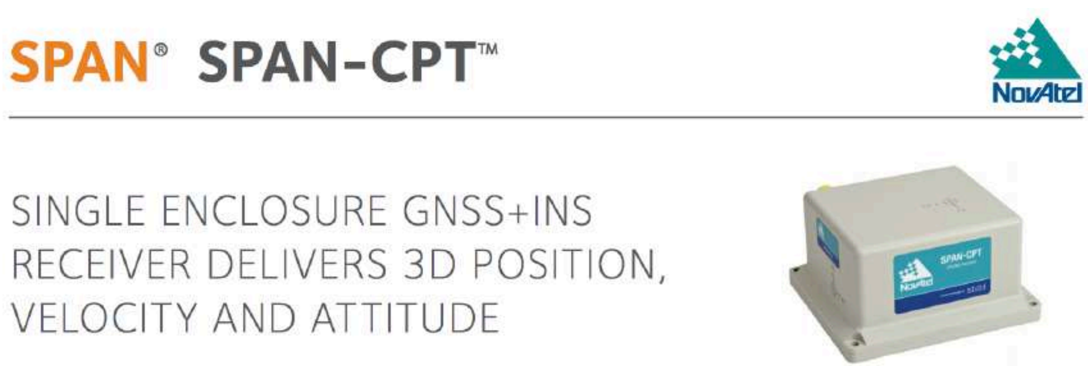
Still degraded by multipath error

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

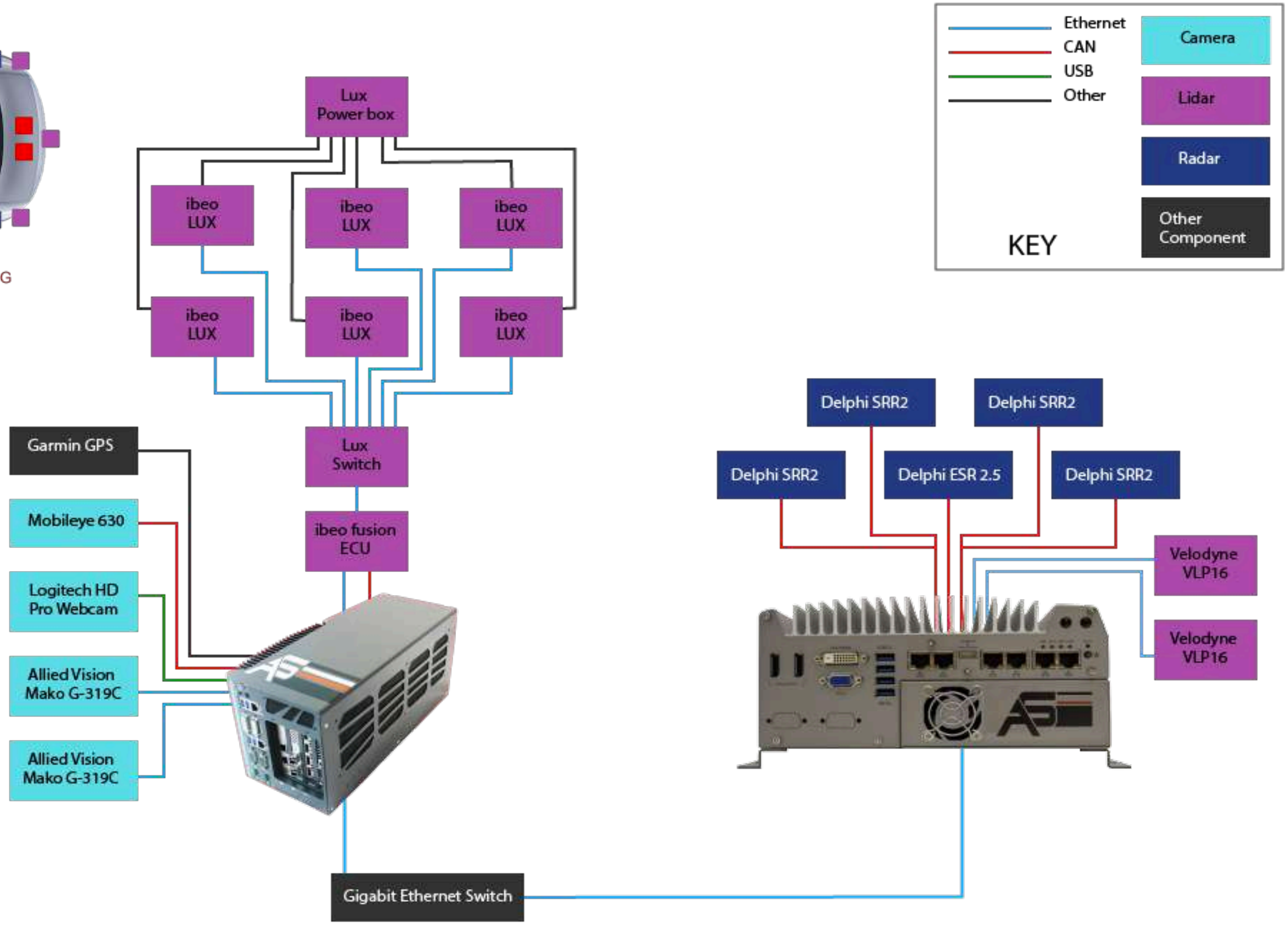
- GPS-700 series antennas (dual-frequency required)
- ANT series antennas (dual-frequency required)
- RF cables–5, 10 and 30 m lengths
- Inertial Explorer post-processing software

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

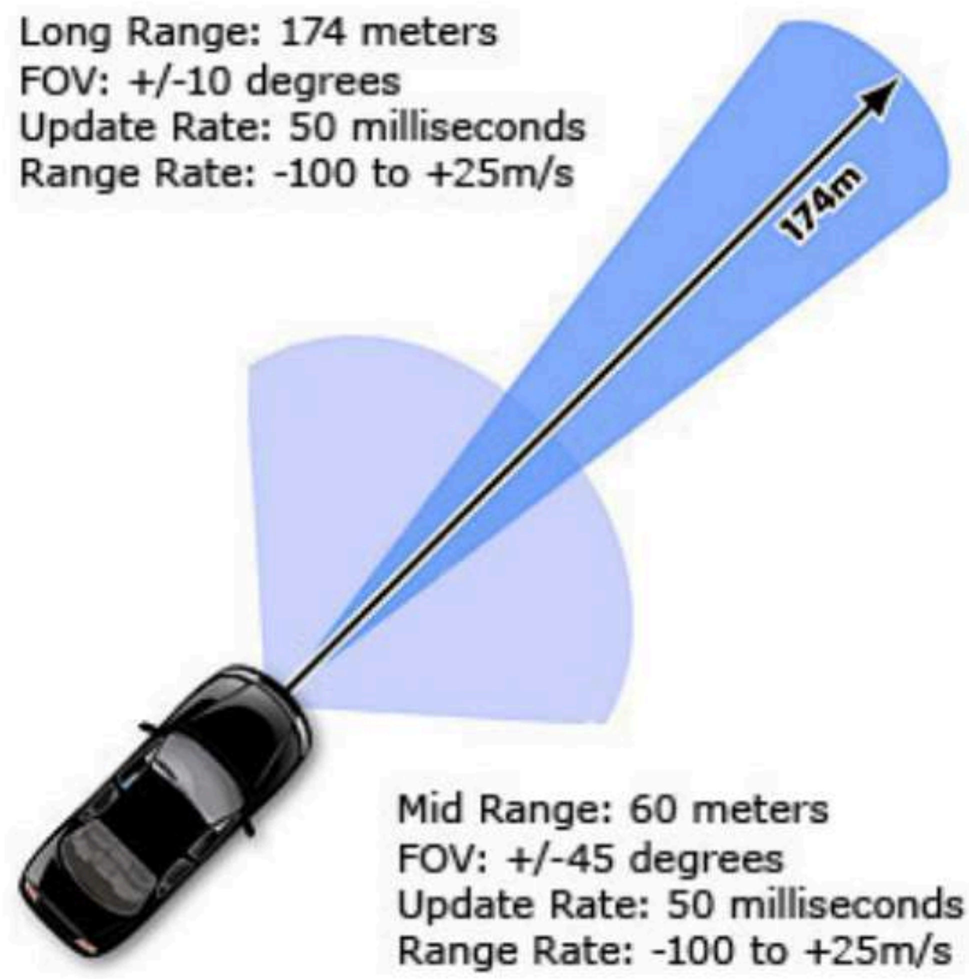


Vehicle Sensors

- Delphi ESR 2.5 Radar

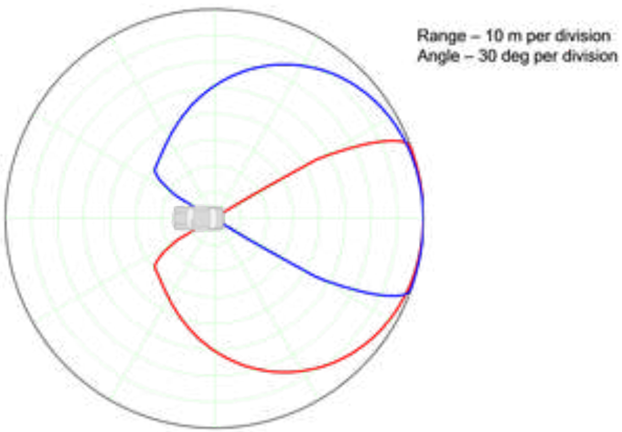
- DEL-ESR-2.5 -24VDC+

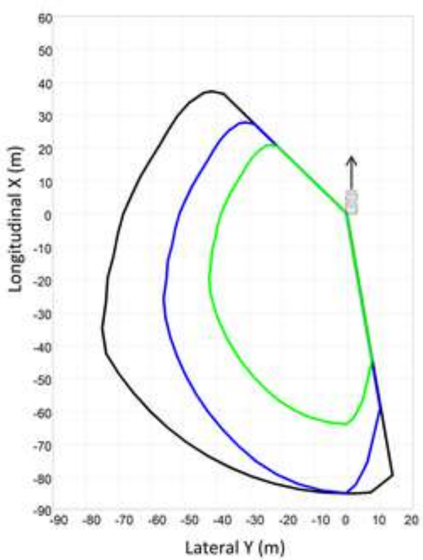
- Delphi's multimode Electronically Scanning RADAR (ESR)

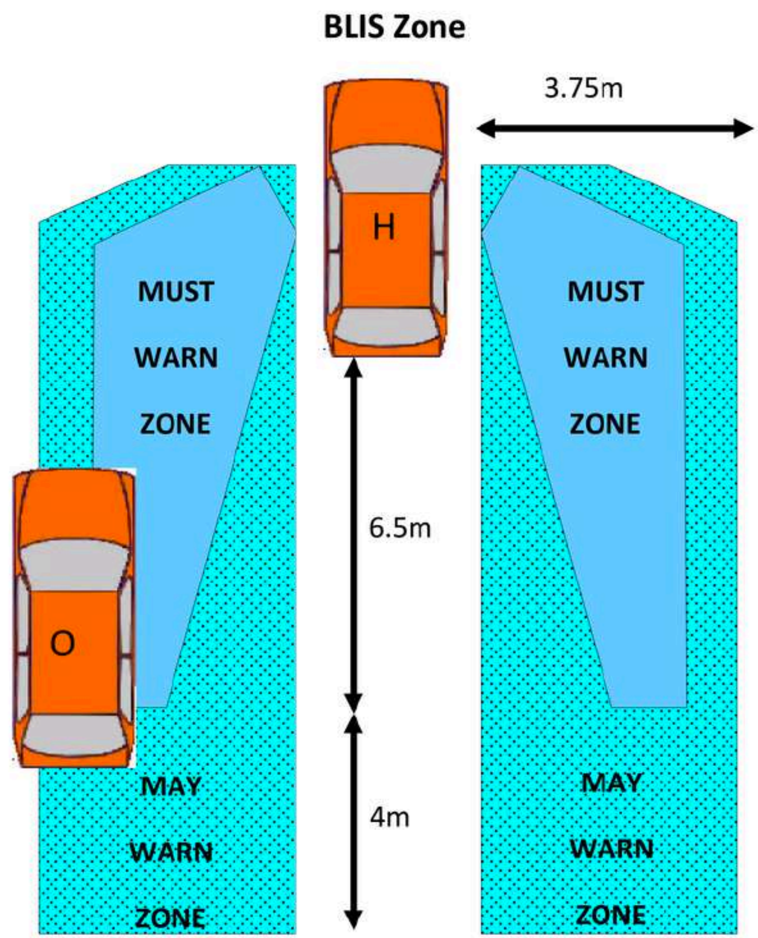


Vehicle Sensors

- 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 *

100 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)