LECTURE 18 – INTRODUCTION TO 3D SENSORS

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CIVE 497/700 Smart Structure Technology

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SDIC
SHAPING SMART INFRASTRUCTURE

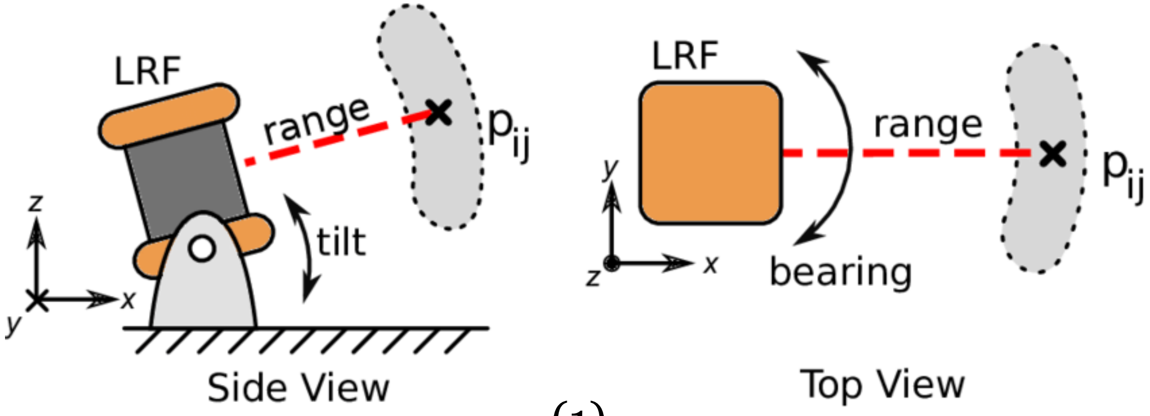
OUTLINE

- What is a 3D sensor?
- Common Types of 3D sensors
- How do they work?
  - Lidars
  - Terrestrial laser scanners
  - Passive stereo vision
  - Active stereo vision
- Overview of 3D mapping at SDIC
  - Mapping
  - Inspection
  - More…

WHAT IS A 3D SENSOR?

- A device that can measure x, y, z coordinates of each point being observed
- Data can be returned in three different formats:

1. Range, with two angles (bearing and azimuth)`
2. Depth Image
3. x, y, z coordinates



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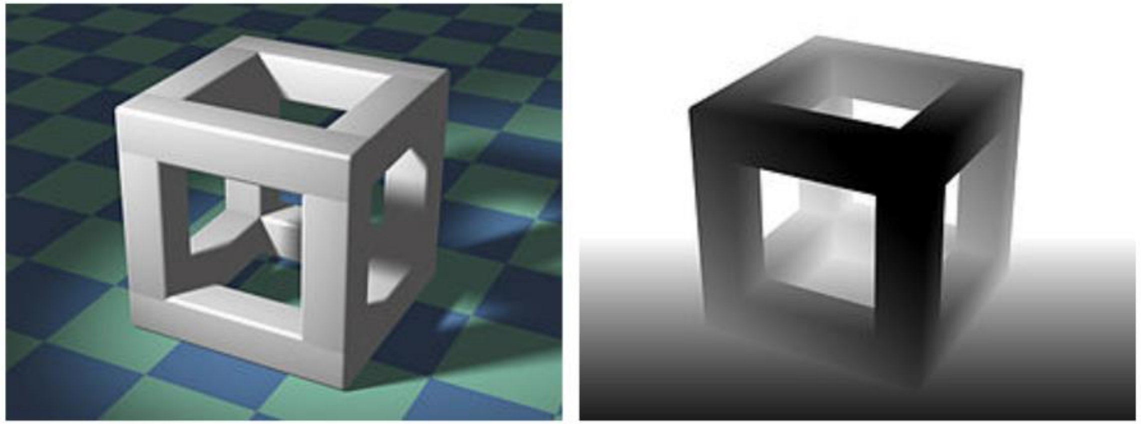

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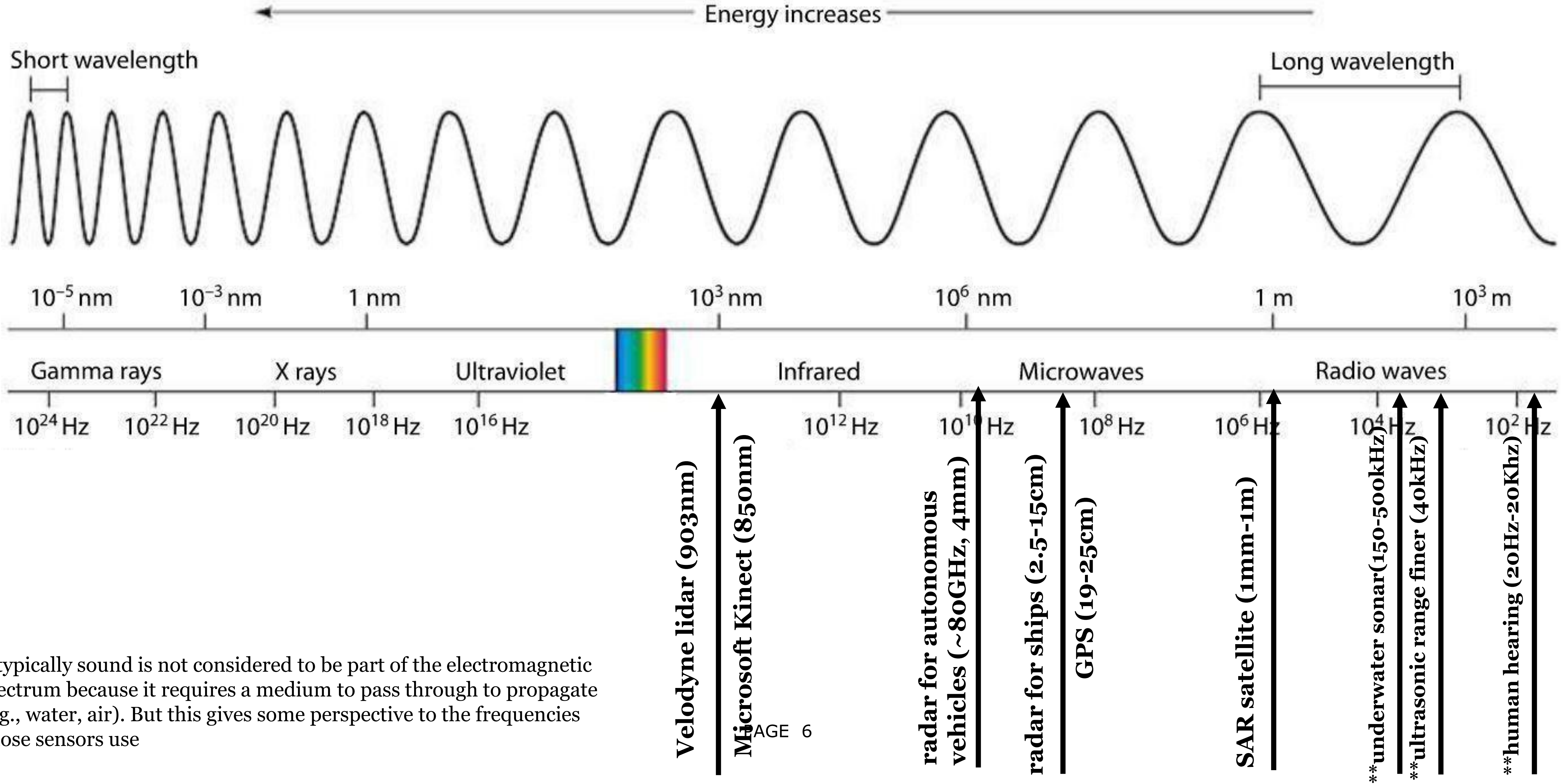
WHAT IS A 3D SENSOR?

- Can be divided into two types:
  1. Active: Emits its own source of energy, and uses this energy to make measurements
     - E.g., radar, sonar
     - Pros: less dependent on the environment, often allows for more precise measurements
     - Cons: higher power consumption, typically more expensive, sometimes suffers from signal interference
  2. Passive: Uses ambient energy in the environment to make measurements
     - E.g., visible spectrum camera, infrared (IR) spectrum camera
     - Pros: low power consumption, less expensive
     - Cons: relies on having sufficient ambient energy, often noisy measurements

COMMON ACTIVE 3D SENSORS

- Time of Flight Sensors:
    - Lidars (Light Detection and Ranging)
    - Terrestrial Laser Scanners (TLS)
    - Radar
    - Sonar
- Active Stereo Vision (or Structured Light)

COMMON ACTIVE 3D SENSORS

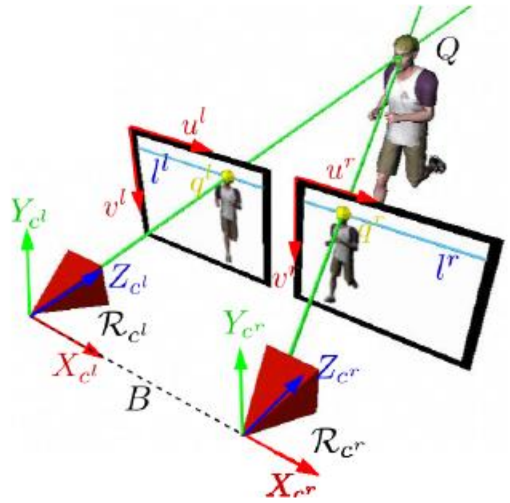


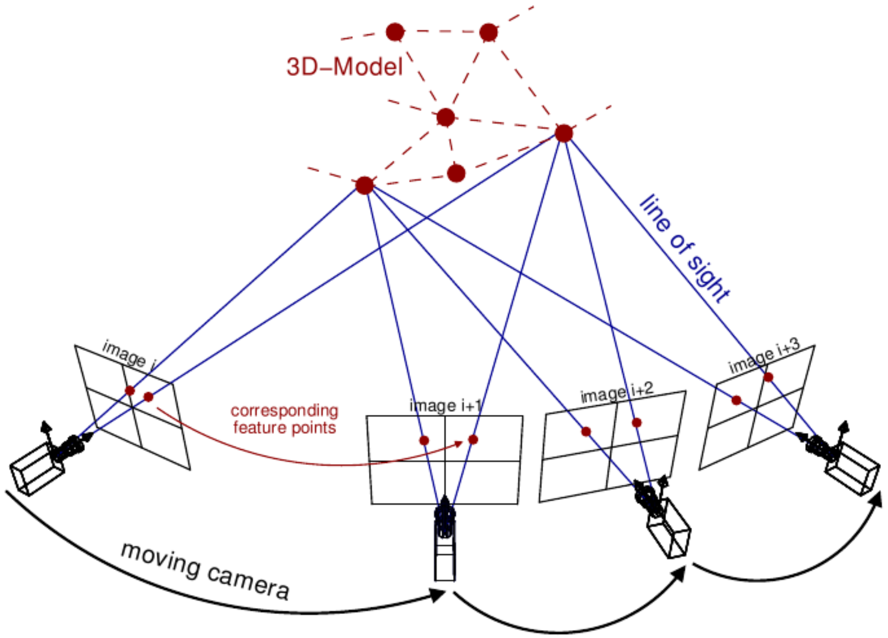
**typically sound is not considered to be part of the electromagnetic spectrum because it requires a medium to pass through to propagate (e.g., water, air). But this gives some perspective to the frequencies Those sensors use

COMMON PASSIVE 3D SENSORS

- Passive stereo camera
- Monocular camera
    - SfM*
    - Visual inertial odometry (VIO)*
    - Visual SLAM*
- Digital Image correlation (DIC)
    - Stereo
    - Monocular*

*All these require an additional 3D sensor to recover scale (e.g., GPS, Inertial Measurement Unit – IMU)



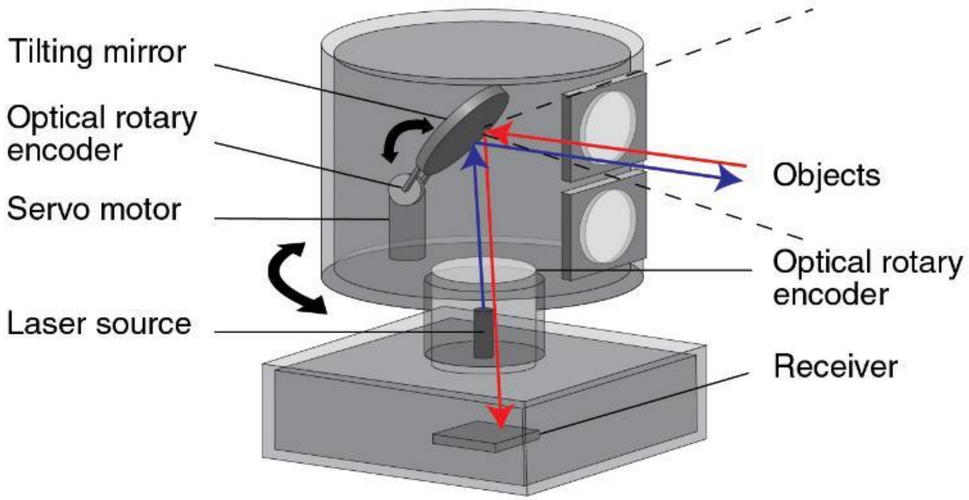


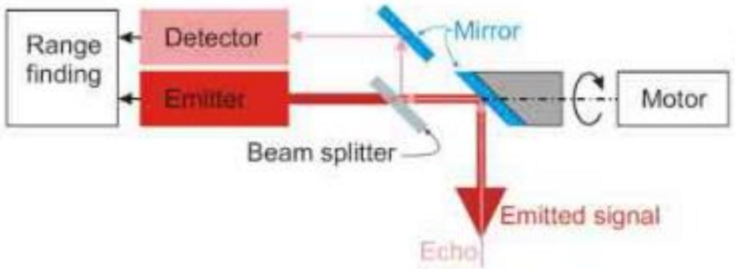
COMMON 3D SENSORS

- We will look at the following 3D sensors in more detail:
  1. Light Detection and Ranging (Lidar) – TOF
  2. Terrestrial Laser Scanners (TLS) - TOF
  3. Passive stereo cameras
  4. Active stereo cameras (Structured Light)
- These are some of the most common 3D sensors used for mapping in civil engineering applications

LIDAR | HOW DOES IT WORK?

- TOF: emit IR pulse and measure the time for the pulse to return
- Rotating mirrors used to direct light beams for discrete scan locations





LIDAR | TYPES

- 2D – Single Beam:
  - One light beam
  - Often beam rotates to get up to 360 degrees of coverage
  - Examples:



  - Devices can be rotated or spun to get 3D coverage


LIDAR | TYPES

- 3D – Multi-Beam:
  - Multiple rotating light beam
  - Examples:

Velodyne

Cepton

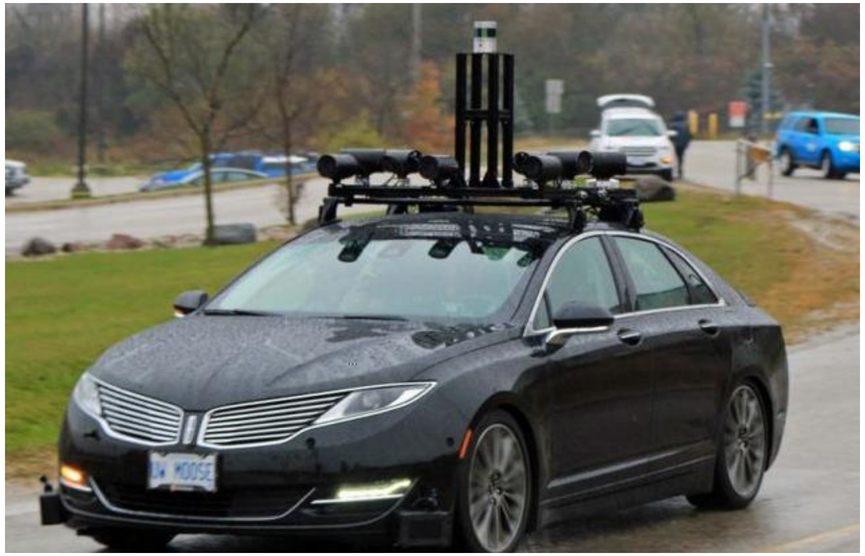
Quanergy

Waymo (Google)

  - Can also be rotated for better coverage

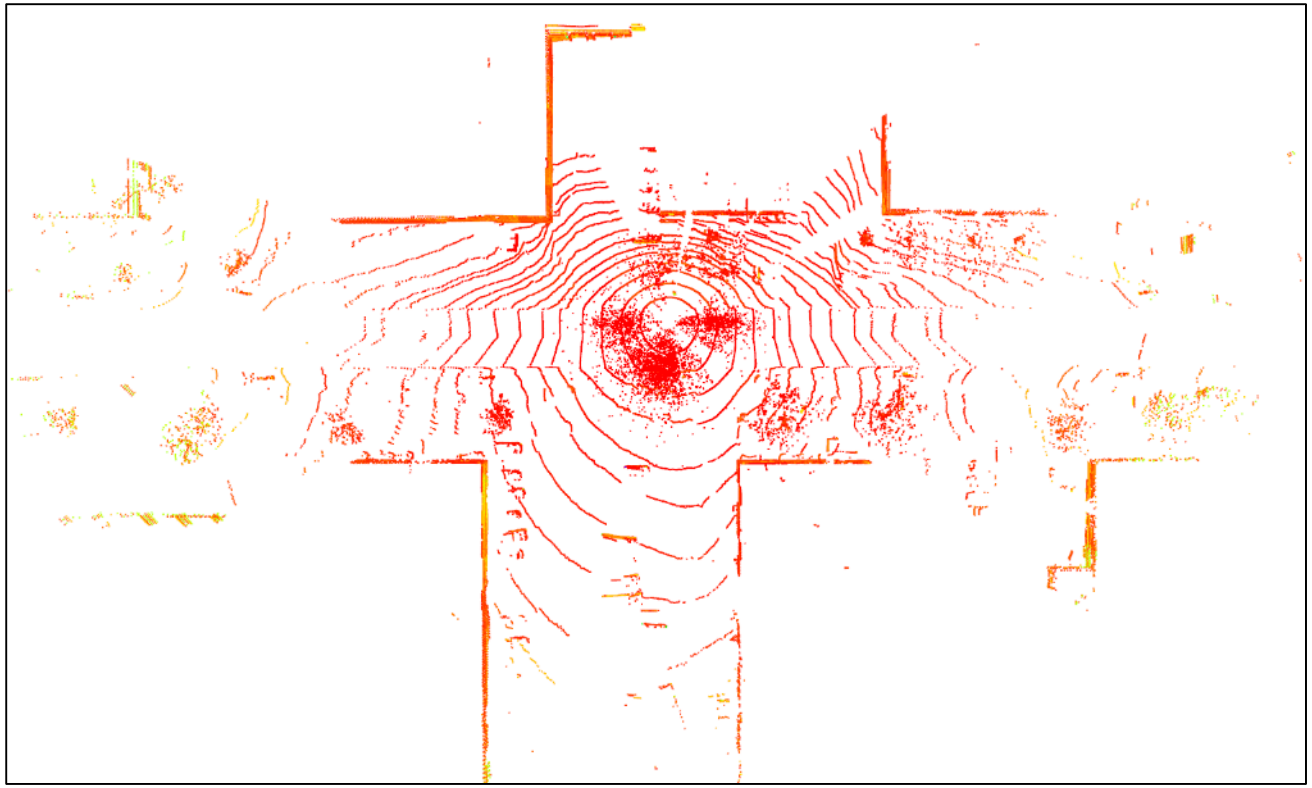
LIDAR | APPLICATIONS

- Autonomous Vehicles

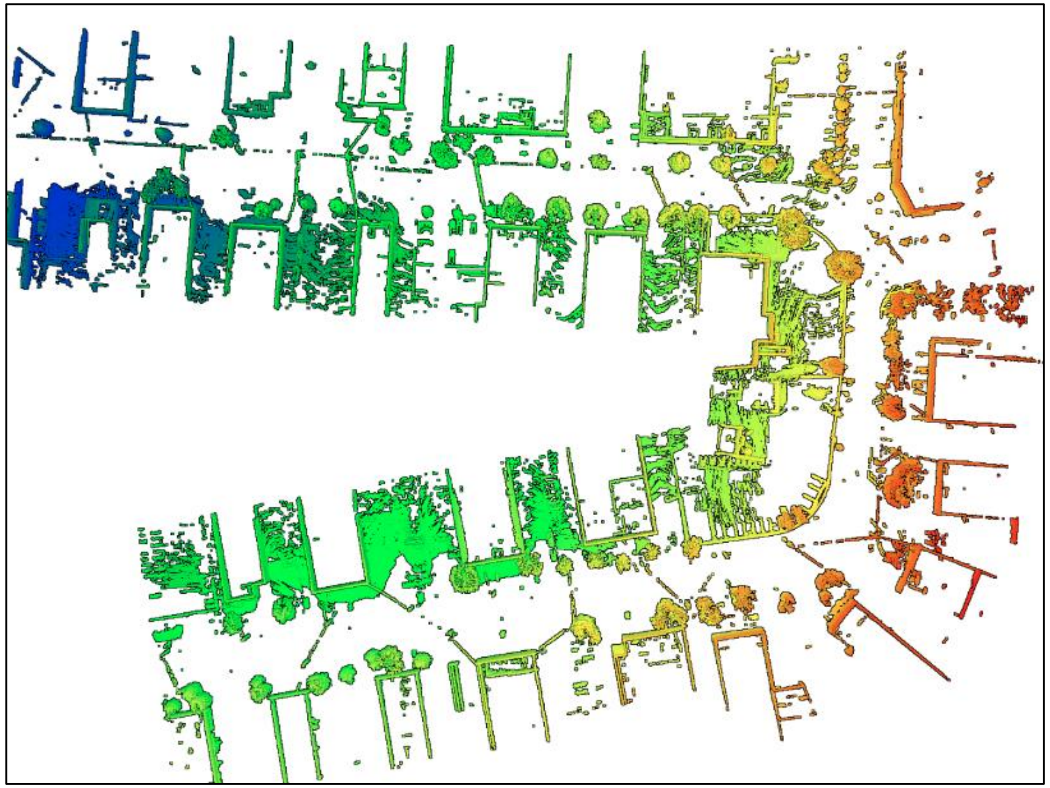



LIDAR | APPLICATIONS

- Autonomous Vehicles



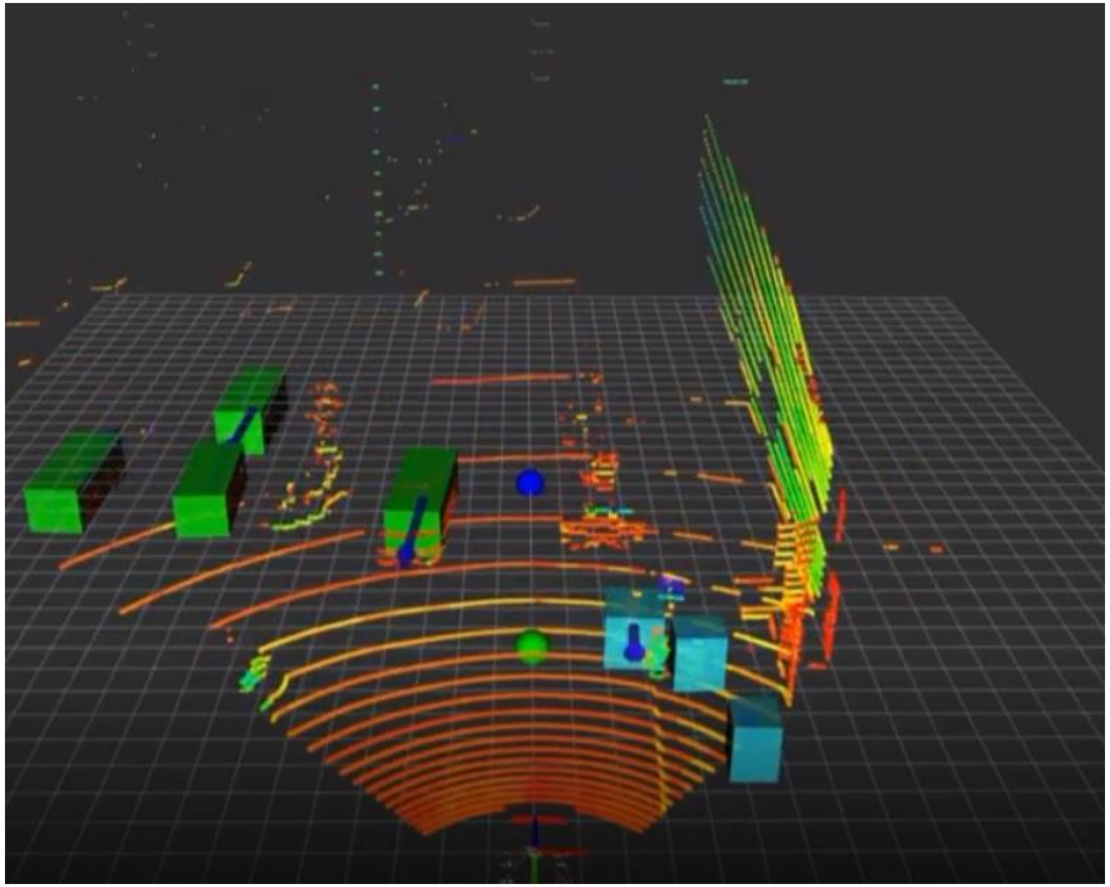
Single Lidar Scan (Autonomoose)



Lidar Map (Autonomoose)

LIDAR | APPLICATIONS

- Autonomous Vehicles



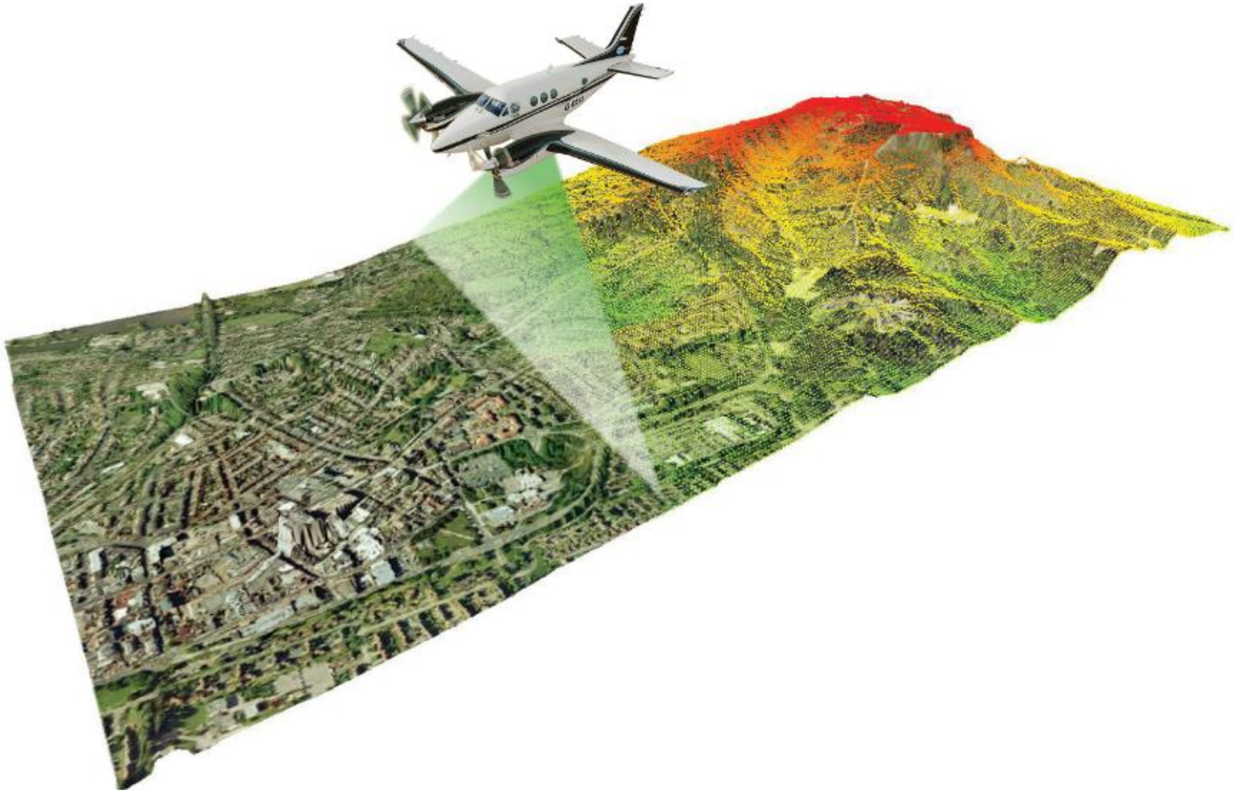
Autonomous Vehicle Perception (Autonomoose)

LIDAR | APPLICATIONS

- Robot Localization and Navigation


LIDAR | APPLICATIONS

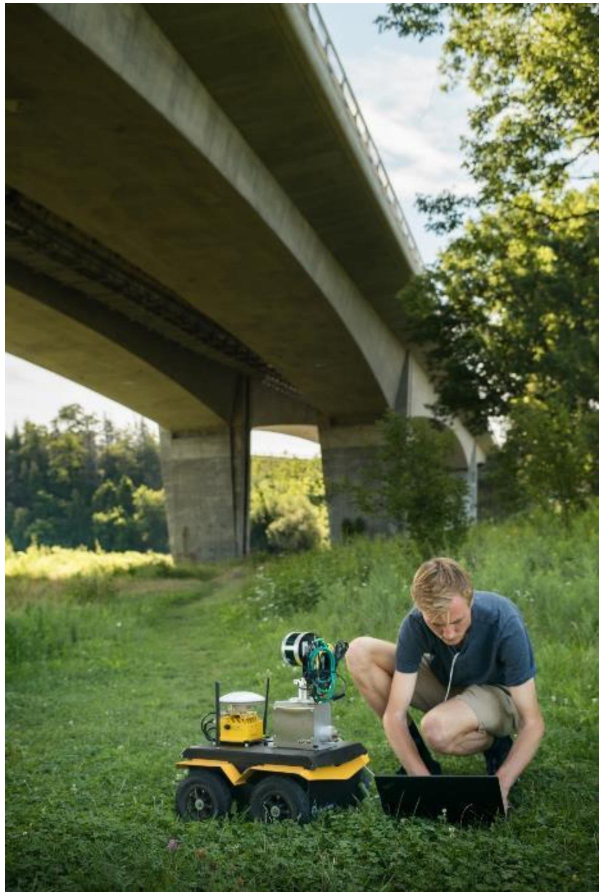
- Outdoor Aerial Mapping



LIDAR | APPLICATIONS

- Indoor Mapping & Inspection

- We will come back to this…



OUTLINE

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- Common Types of 3D sensors
- How do they work?
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- Overview of 3D mapping at SDIC
  - Mapping
  - Inspection
  - More…

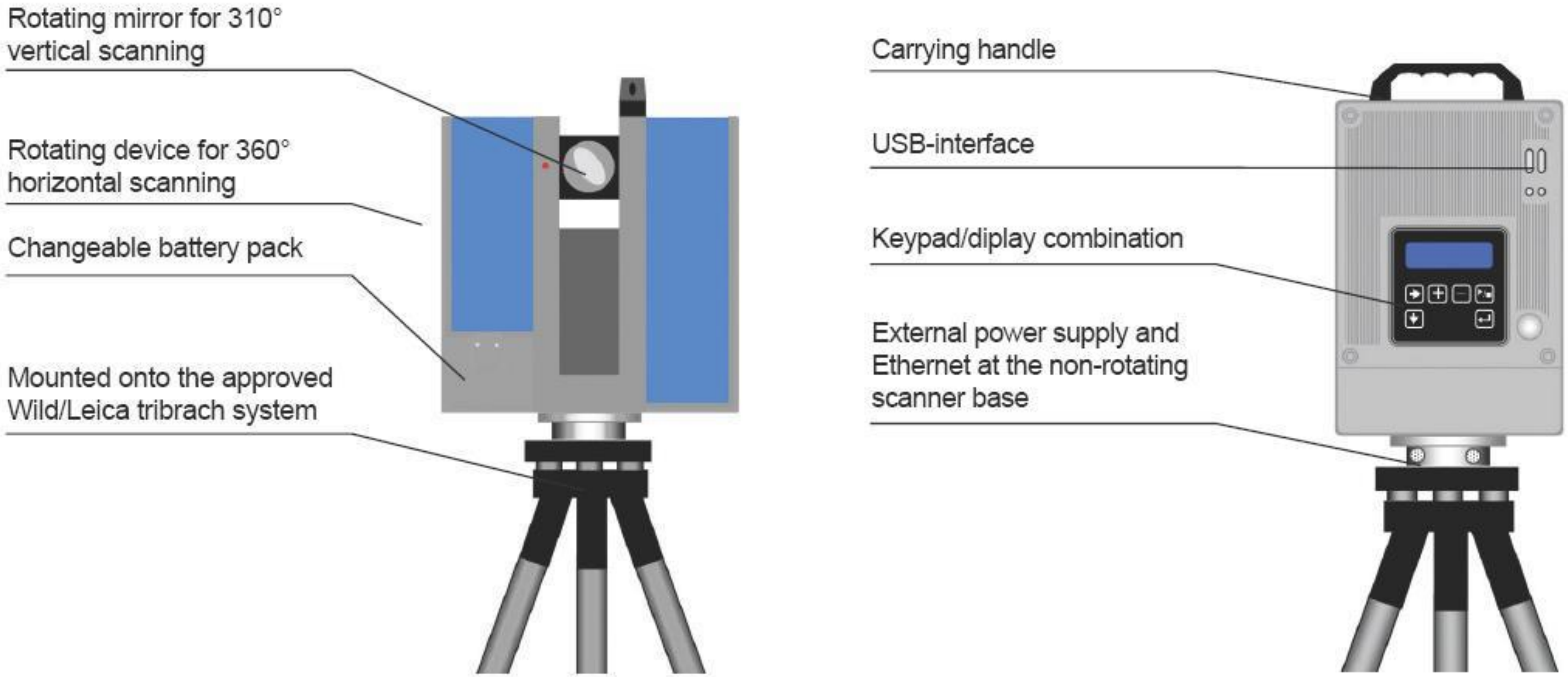
TERRESTRIAL LASER SCANNER | TYPES

Faro Focus

Leica ScanStation

TERRESTRIAL LASER SCANNER | HOW DOES IT WORK?

- TOF: emit IR signal and measure the time for the signal to return
- Rotating mirrors used to direct light beams for discrete scan locations
- RGB camera to colour points



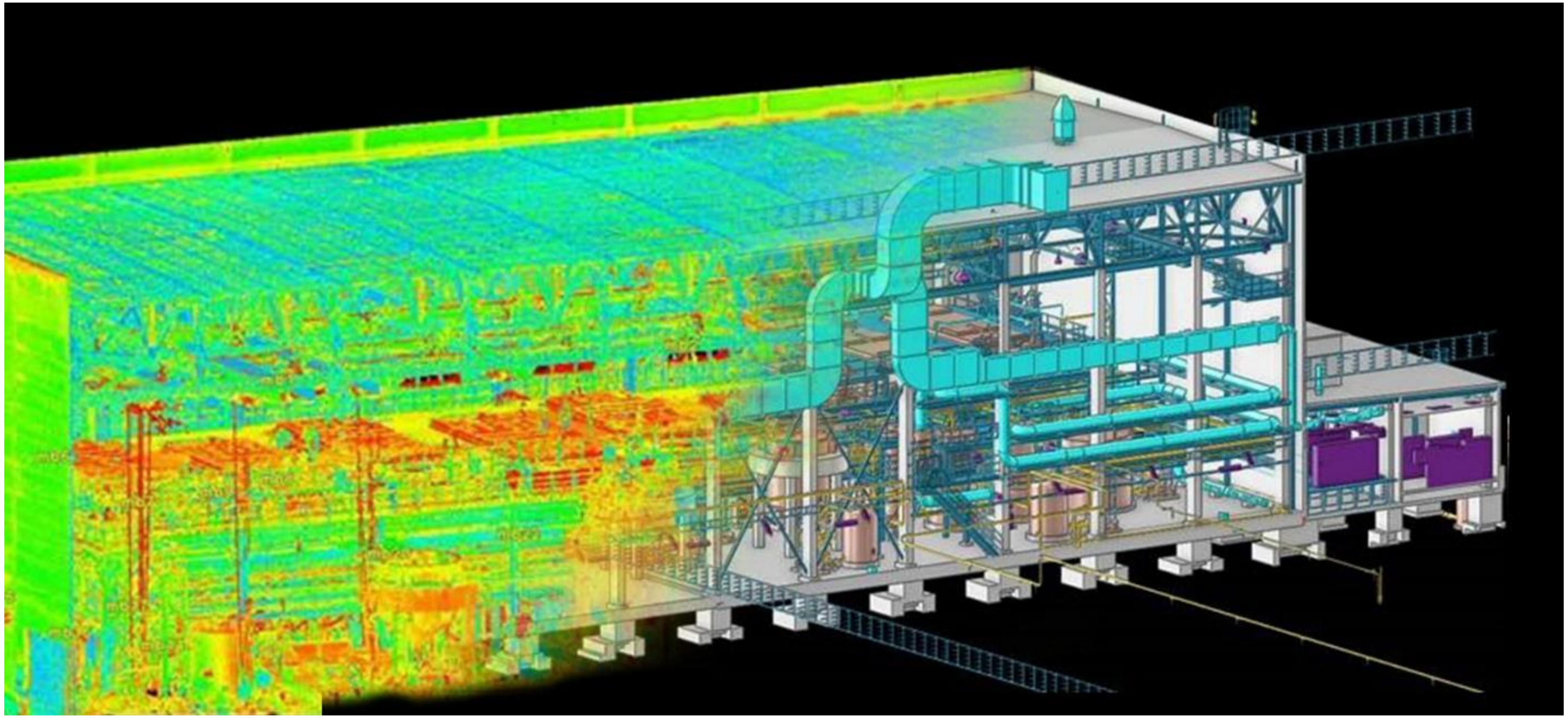
TERRESTRIAL LASER SCANNER | RESULTS

TERRESTRIAL LASER SCANNER | APPLICATIONS

- Forensics and scene reconstruction

TERRESTRIAL LASER SCANNER | APPLICATIONS

- Scan to BIM for:
  - As-built drawings
  - New drawings of old facilities



TLS VS LIDAR

	Lidar (Velodyne Ultra Puck)	TLS (Faro Focus3D 130)
Accuracy	~2-3cm	~2mm
Range	100m	130m
Data collection rate (pts/s)	300,000	122,000-976,000
Vertical FOV	40°	300°
Horizontal FOV	360°	360°
Weight	0.9kg	5.2kg
Built-in camera?	no	yes
Cost (USD)	$4,000	$20,000

Why such a big difference with accuracy?

TLS VS LIDAR

- There are two common ways to measure TOF

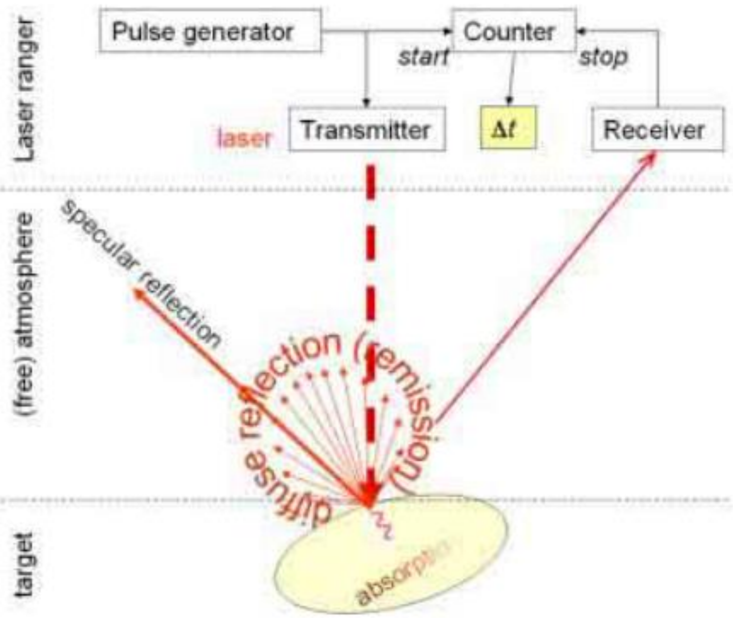
1. Pulse round trip time
   - Less accurate (order of cms)
   - Simpler hardware/processing (easy to add multiple beams)
   - Less expensive (mass production - vehicles)

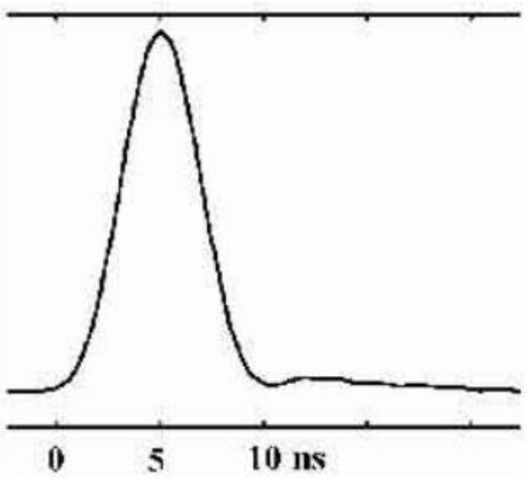
2. Phase shift measurement
   - More accurate (order of mms)
   - More complicated hardware/processing
   - More expensive

TLS VS LIDAR

1. Pulse round trip time
   - Short (few ns) pulse is emitted
   - Counter is started upon emission and stopped when return signal is received
   - Pulse often assumed to be Gaussian shape
   - Multiple peak returns possible
   - Distance calculated using:
   - $r = 0.5 \times c_g \times \Delta t$

   c_g : speed of light





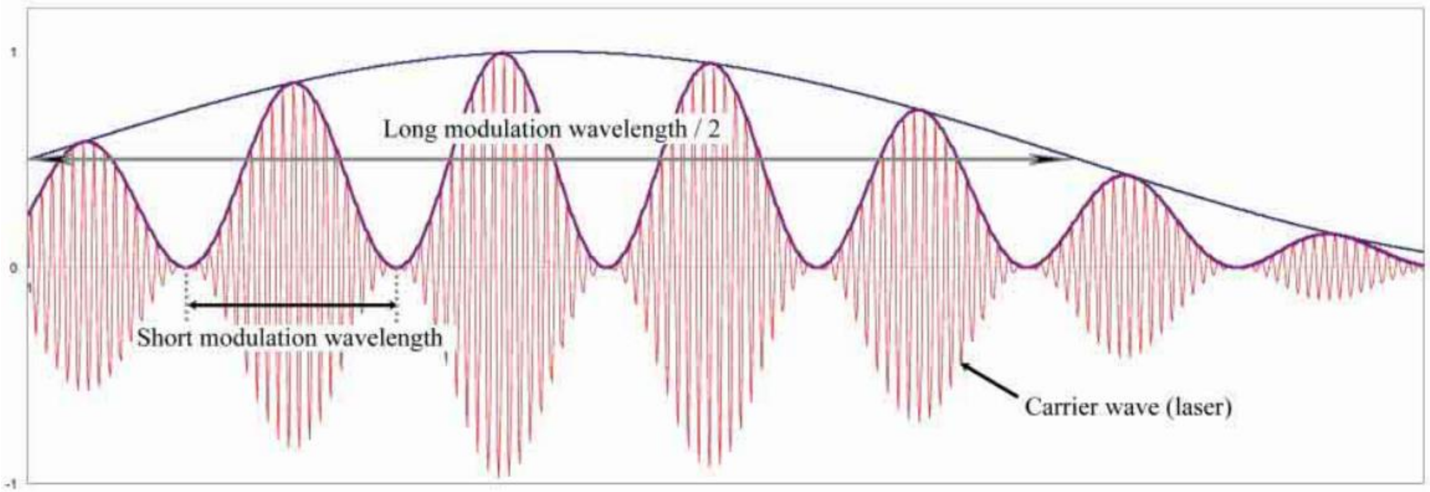
TLS VS LIDAR

2. Phase shift measurement

- A continuous wave laser
- Signal is modulated by amplitude
- Signals produced and emitted are compared and phase offset (in rads) is measured
- Distance can be calculated according to:

$$r = \frac{\Delta\theta}{2\pi}\frac{\lambda}{2} + \frac{\lambda}{2}n$$

- r: range, $\Delta\theta$: change in phase, λ: wavelength, n: number of full wavelengths
- longest wavelength defines the uniqueness range and the shortest wavelength defines the precision (usually about 1% of phase)



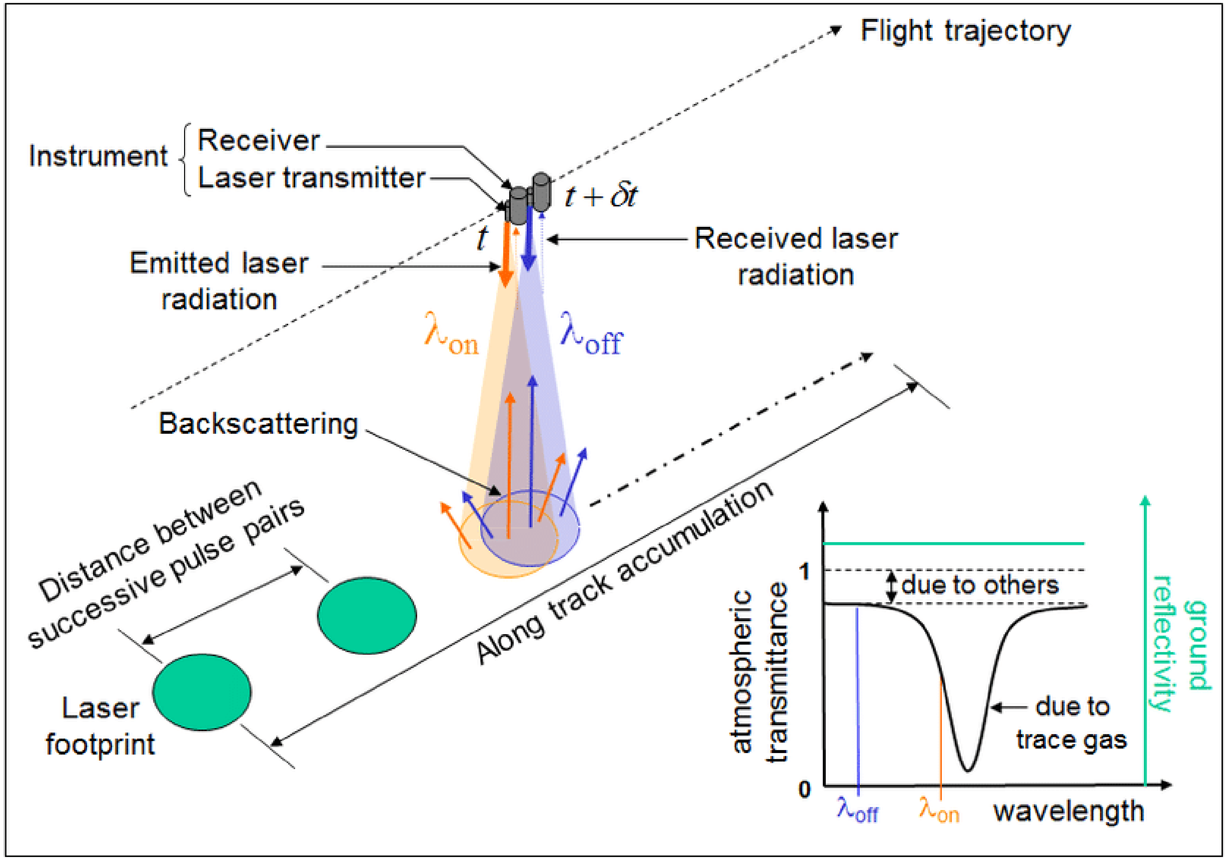
TLS VS LIDAR

Other factors affecting accuracy:

- Atmosphere
- Surface reflectance
- Surface roughness
- Distance to object
- Power of emitted signal

➢ All of these affect the signal to noise ratio

- Increased S/N ratio = increased accuracy



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    - ~~Lidars~~
    - ~~Terrestrial laser scanners~~
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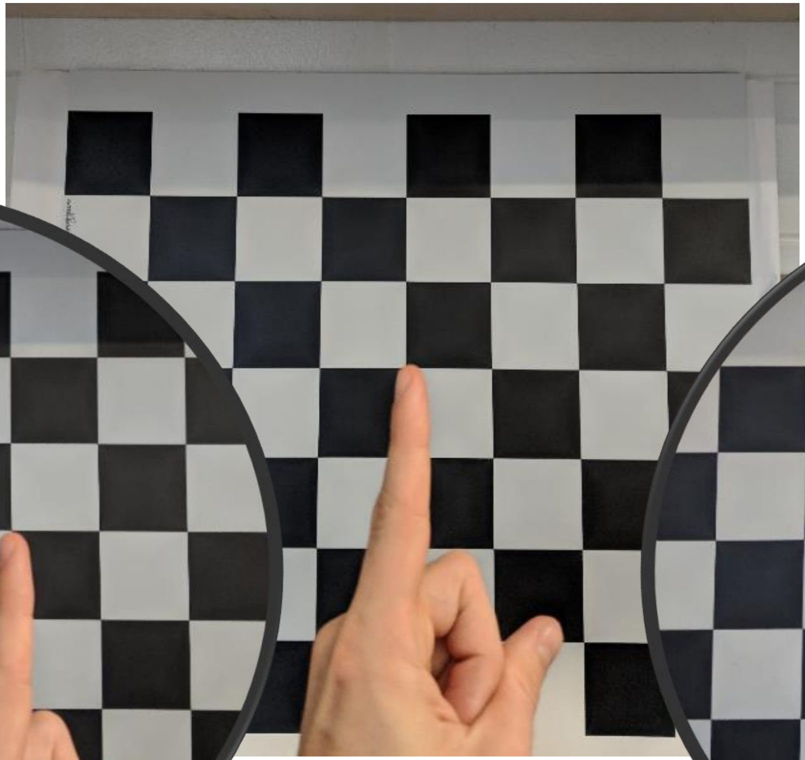
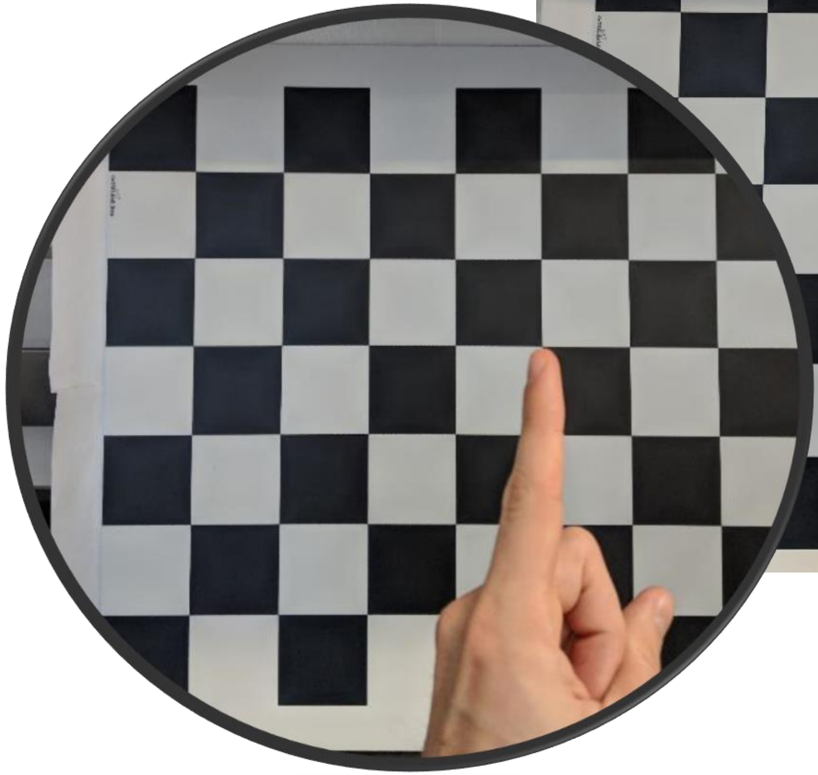
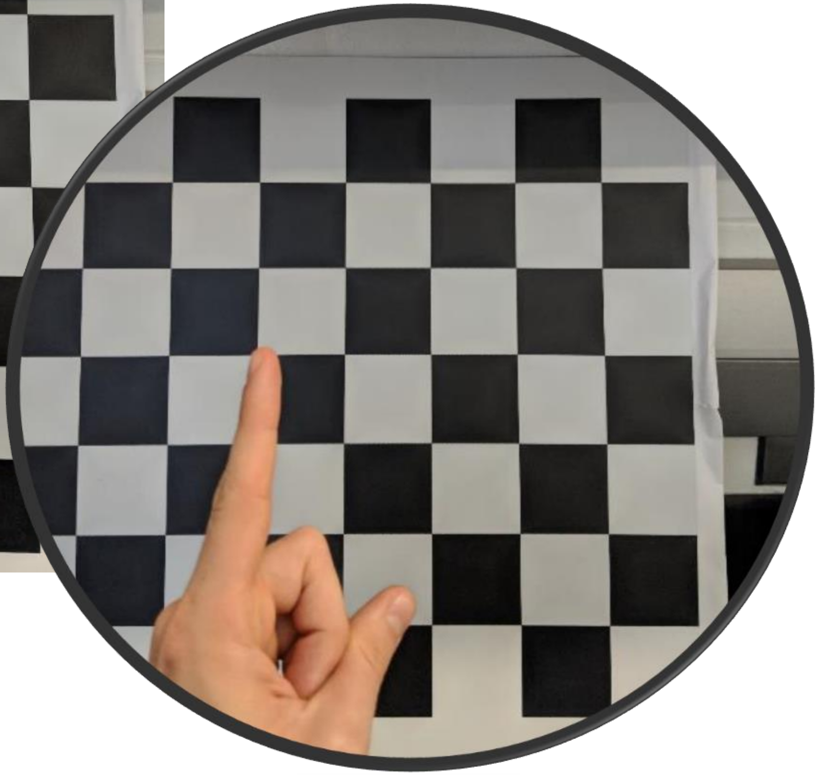
    - Active stereo vision
- Overview of 3D mapping at SDIC
    - Mapping
    - Inspection
    - More…

STEREO CAMERA| EXPERIMENT



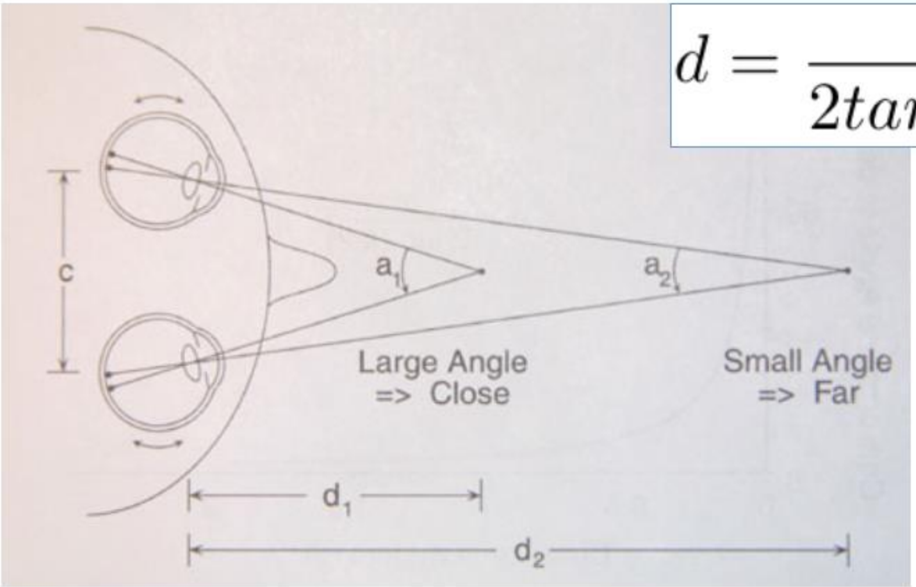


Left Eye



Right Eye

STEREO CAMERA| EXPERIMENT



$$d = \frac{c}{2tan(a/2)}$$

Right Eye

STEREO CAMERA| EXPERIMENT

3D Movies:

STEREO CAMERA| HOW DOES IT WORK?

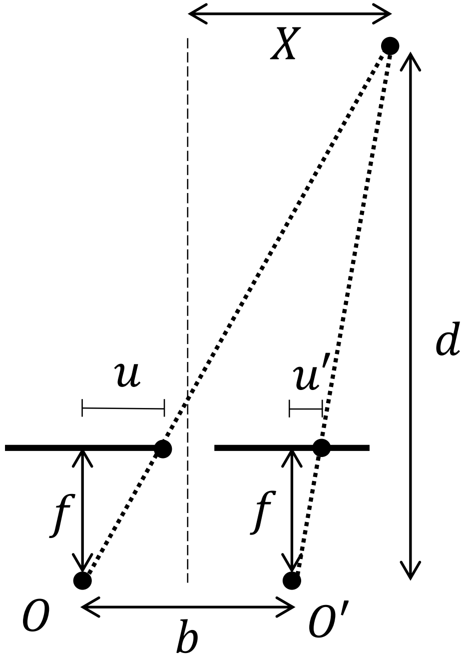
- Triangulation using disparity (for parallel images)
  - Using similar triangles, we can define the following ratios:

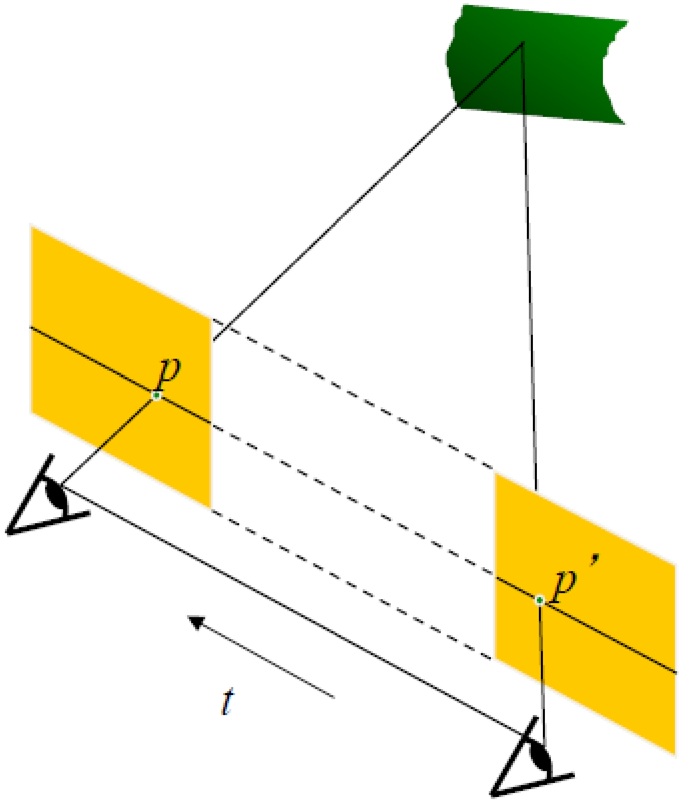
$$\frac{u}{f} = \frac{X + {}^{b}/_{2}}{d} \qquad \frac{u'}{f} = \frac{X - {}^{b}/_{2}}{d}$$

  - Solving for the distance

$$\mathrm{d} = \frac{bf}{u - u'} \qquad disparity = u - u'$$

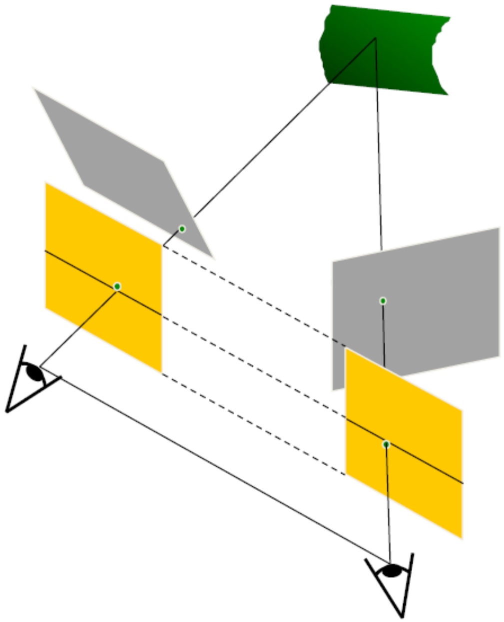
  - Therefore, we can convert a disparity map to a depth image

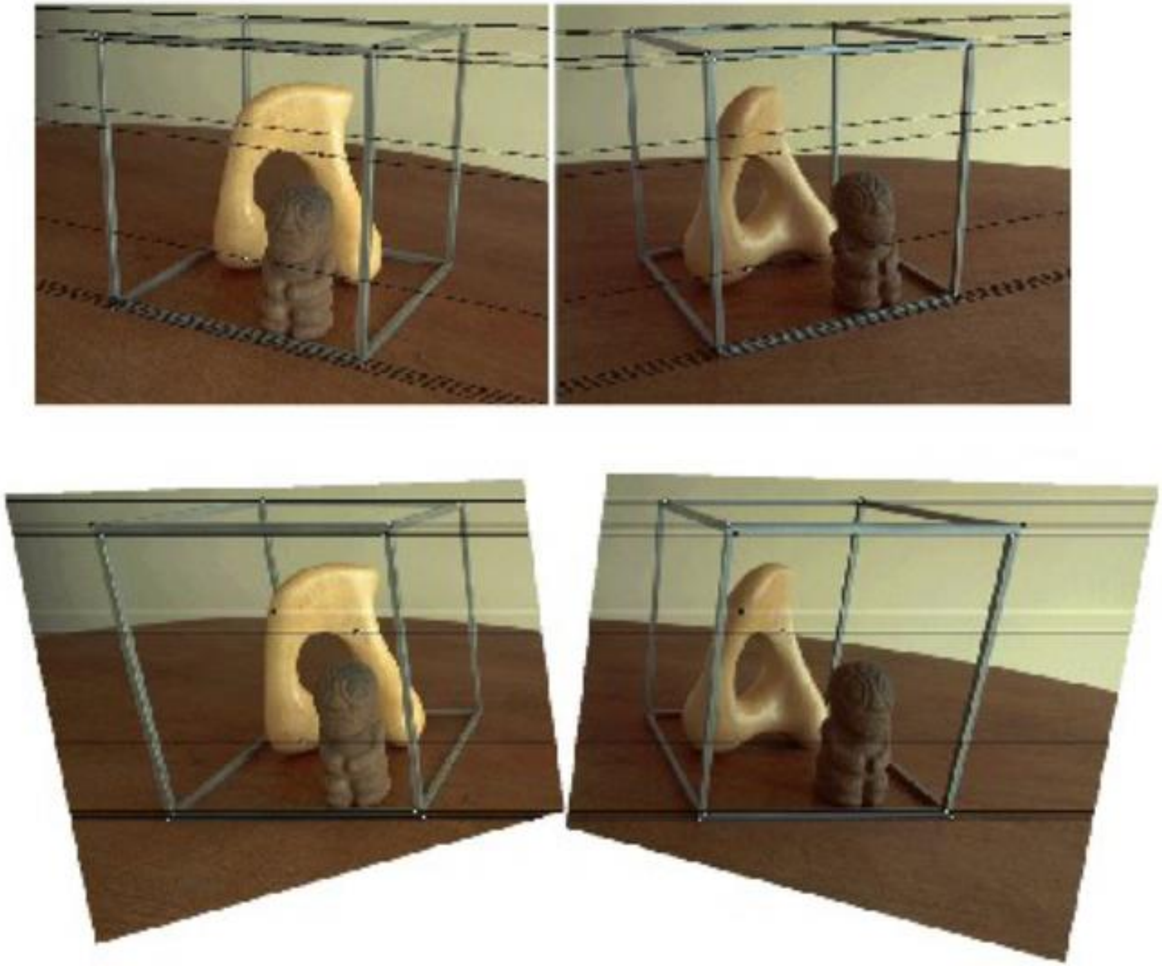




STEREO CAMERA| HOW DOES IT WORK?

- Non-parallel images
  - Use stereo rectification
  - Features correspondence along horizontal line

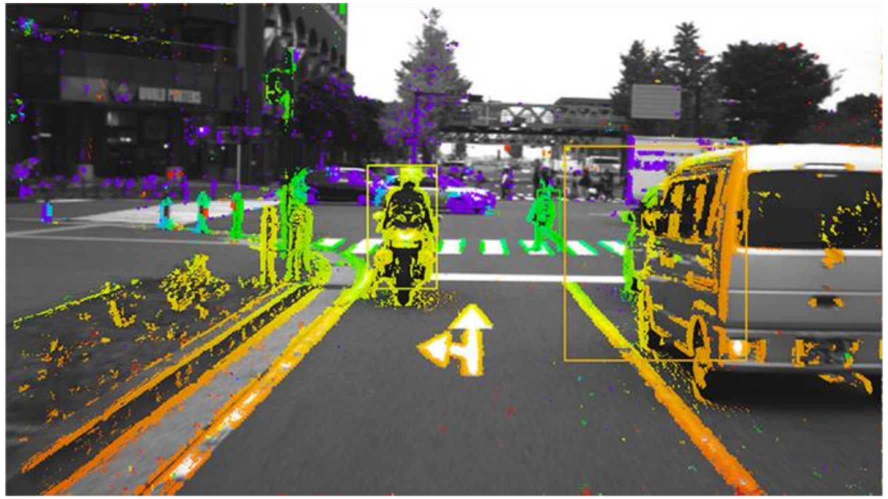




STEREO CAMERA| HOW DOES IT WORK?

- Results:
  - Often not able to get full depth image due to lack of distinct features

Camera image



Disparity image

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    - ~~Passive stereo vision~~
    - Active stereo vision → Structured Light
- Overview of 3D mapping at SDIC
    - Mapping
    - Inspection
    - More…

STRUCTURED LIGHT | COMMON EXAMPLES

- Microsoft Connect

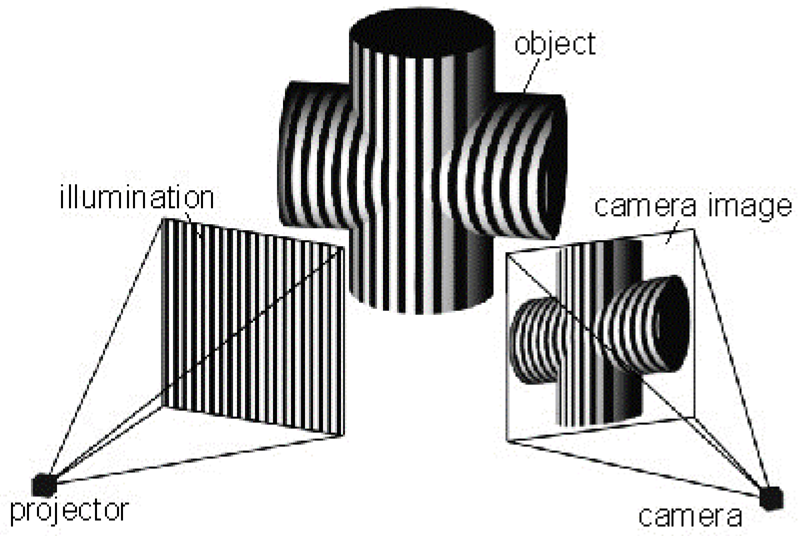
- Structure Sensor

- Intel real-sense

- Google tango

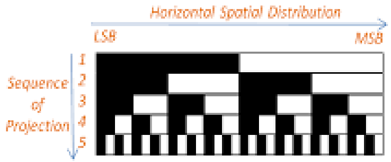
STRUCTURED LIGHT | HOW DOES IT WORK?

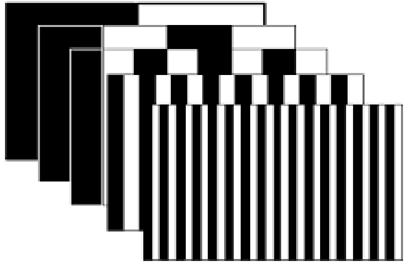
- Projector and camera setup as stereo pair
- Light is projected in a known pattern
- Patterns:
  - horizontal & vertical lines
  - checkerboard
  - dots

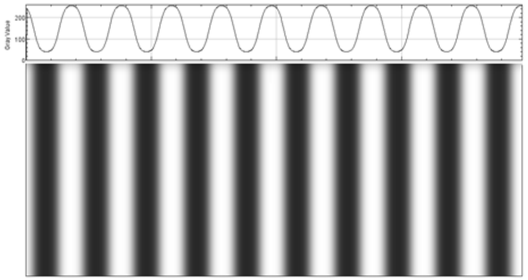


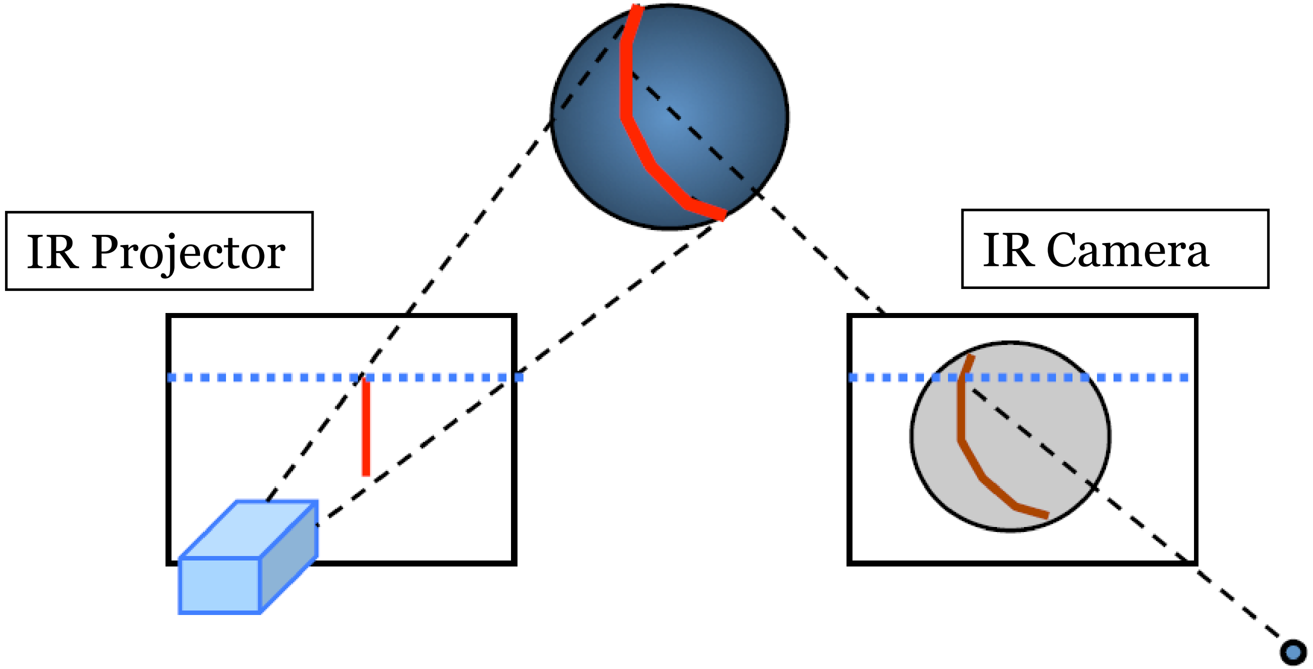
STRUCTURED LIGHT | HOW DOES IT WORK?

- Same procedure as passive stereo: find correspondences, measure disparity and calculate depth
- Correspondence issue solved by analysing projected pattern
- Patterns:









STRUCTURED LIGHT | HOW DOES IT WORK?

- Results:

Pros:

- Fast
- Inexpensive
- Accurate for close range
- Full depth map (as opposed to passive stereo)

Cons:

- Short range only (3-6m depending on sensor)
- Easily corrupted by ambient light
  - Cannot use outside in the sun
  - Inherently low signal to noise ratio due to the amount of light that needs to be projected

EXTRA SLIDES

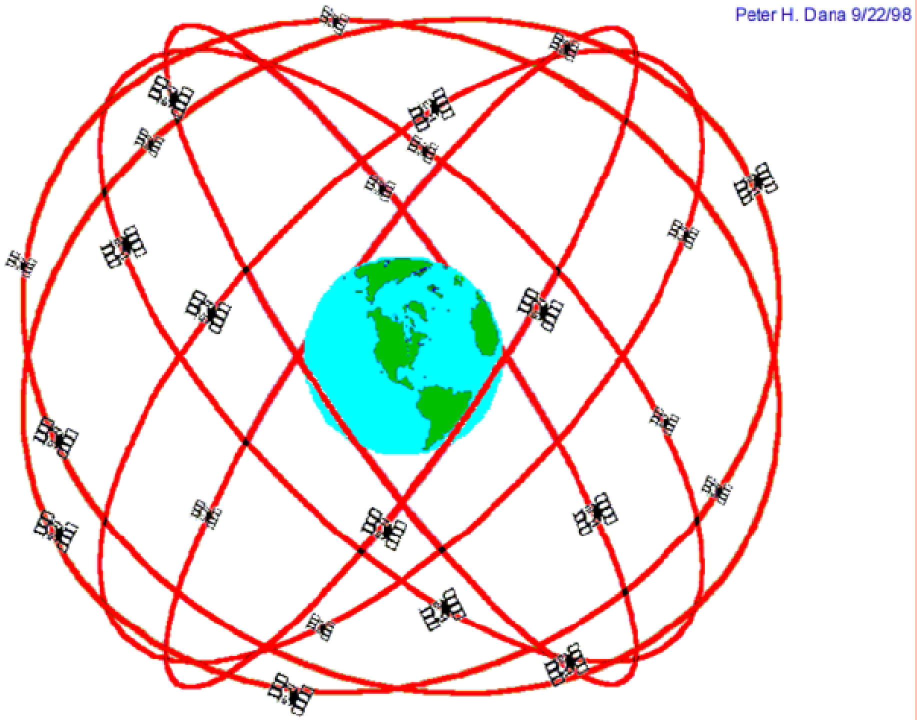
EXTRA INFORMATION | GPS AND IMU

- Other important 3D sensors that are very common are GPS and IMU
- These following slides will present the two technologies for those that are curious
- These slides were taken from ME640 – Autonomous Mobile robotics by Dr. Steven L. Waslander

Position Sensors

- **Global Positioning System (GPS)**

- Position determined based on time of flight
  - Need 4 geometrically distributed sources
  - Need 1 nanosecond timing for sub-meter position resolution



GPS Nominal Constellation
24 Satellites in 6 Orbital Planes
4 Satellites in each Plane
20,200 km Altitudes, 55 Degree Inclination

12 hour period

Source: Steven Waslander, ME640 2018

Position Sensors

- **How can GPS possibly work?!**

- Minimal power
  - Satellites produce ~500 Watt signals
  - Receivers see as little as -160 dBW signal (10^{-16} Watts)

- Precise Satellite position information
  - V_{sv} = 3.9 km/s in ECEF

- Precise timing
  - 1 μsec = 300 m range error
  - Satellite relativistic effect = 38 μsec/day or 12 km error!
    - +45 μsec/day General Relativity: clocks faster in lower gravity
    - -7 μsec/day Special Relativity: clocks slower at higher velocity

- Consistent earth model
  - Rotation axis varies
  - Elliptical shape is an approximation
  - Gravity not constant at mean sea level or normal to surface

Source: Steven Waslander, ME640 2018

Position Sensors

- **But GPS does work after all!**

- Can manage on minimal power
  - Gold Codes allow tracking of extremely weak signals

- Precise satellite positions available
  - Control Segment estimates orbital parameters to 2 m position accuracy

- Precise timing feasible
  - Satellites use rubidium and cesium clocks (drift 10^{-9} s/day)

- Thanks to Einstein for figuring out relativity

- WGS84 earth model
  - WGS84 standard defines ECEF coordinates, earth shape and vertical direction

Source: Steven Waslander, ME640 2018

Position Sensors

- GPS Hardware

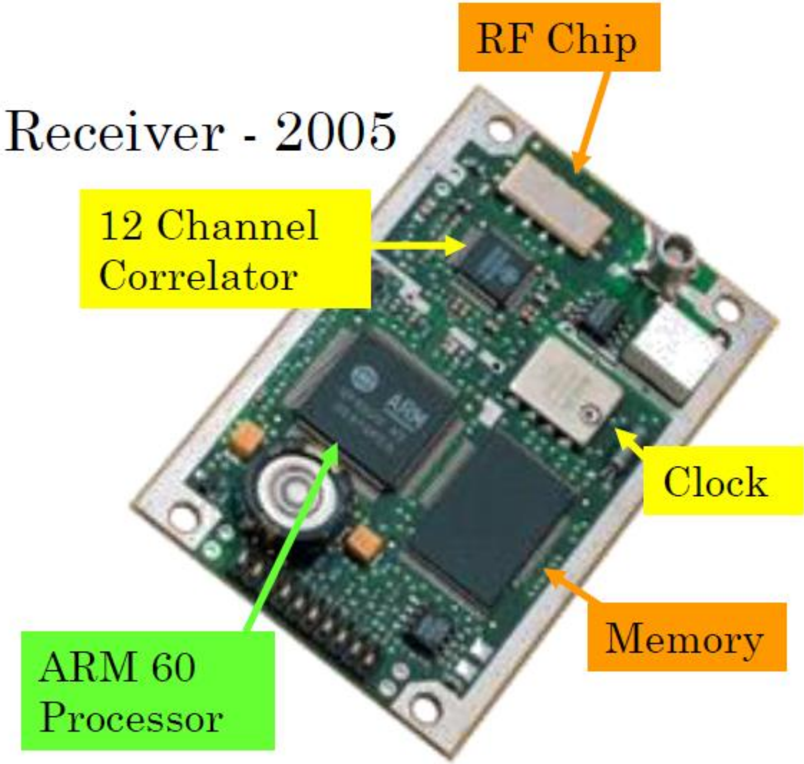
Space Vehicle (SV)

GPS Block II-F satellite

Control Segment (CS)

Satellite-tracking-station on Hawaii

Receiver - 2005



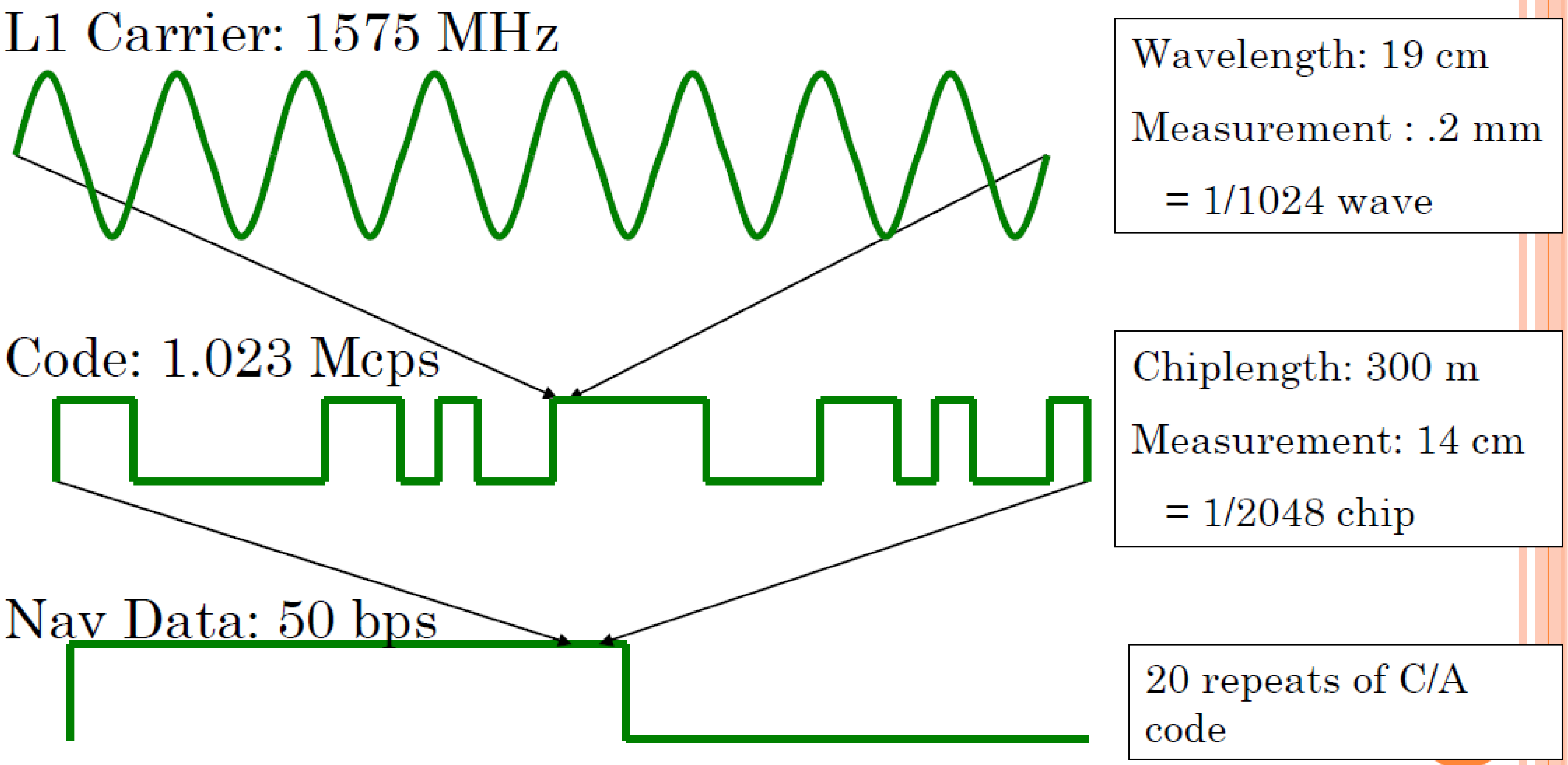
Novatel Superstar II

Receiver - 2015

Source: Steven Waslander, ME640 2018

Position Sensors

- GPS Satellite Signals
  - Travel at light speed, *c*

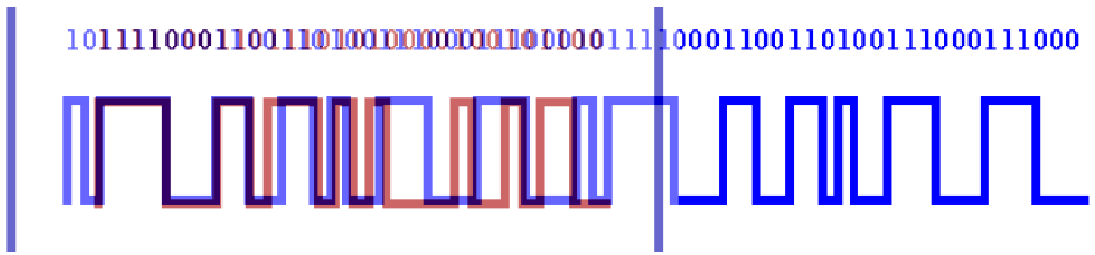


Source: Steven Waslander, ME640 2018

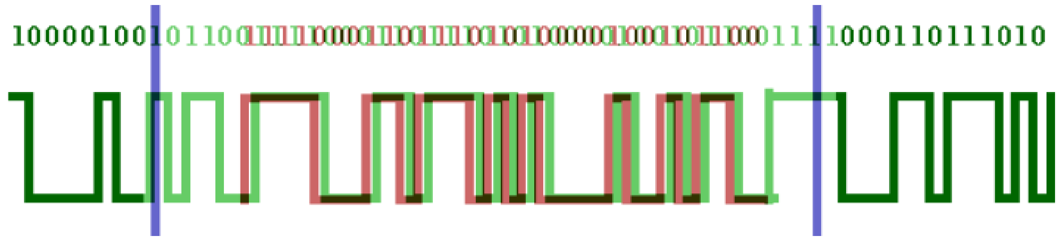
Position Sensors

- GPS Signal correlation
  - 32 unique 1024 chip gold codes which are orthogonal

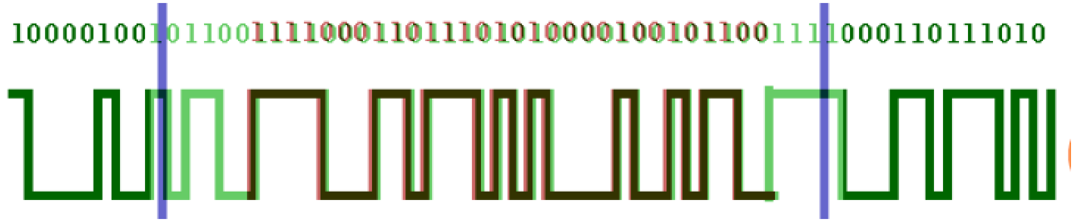
- None



- Half



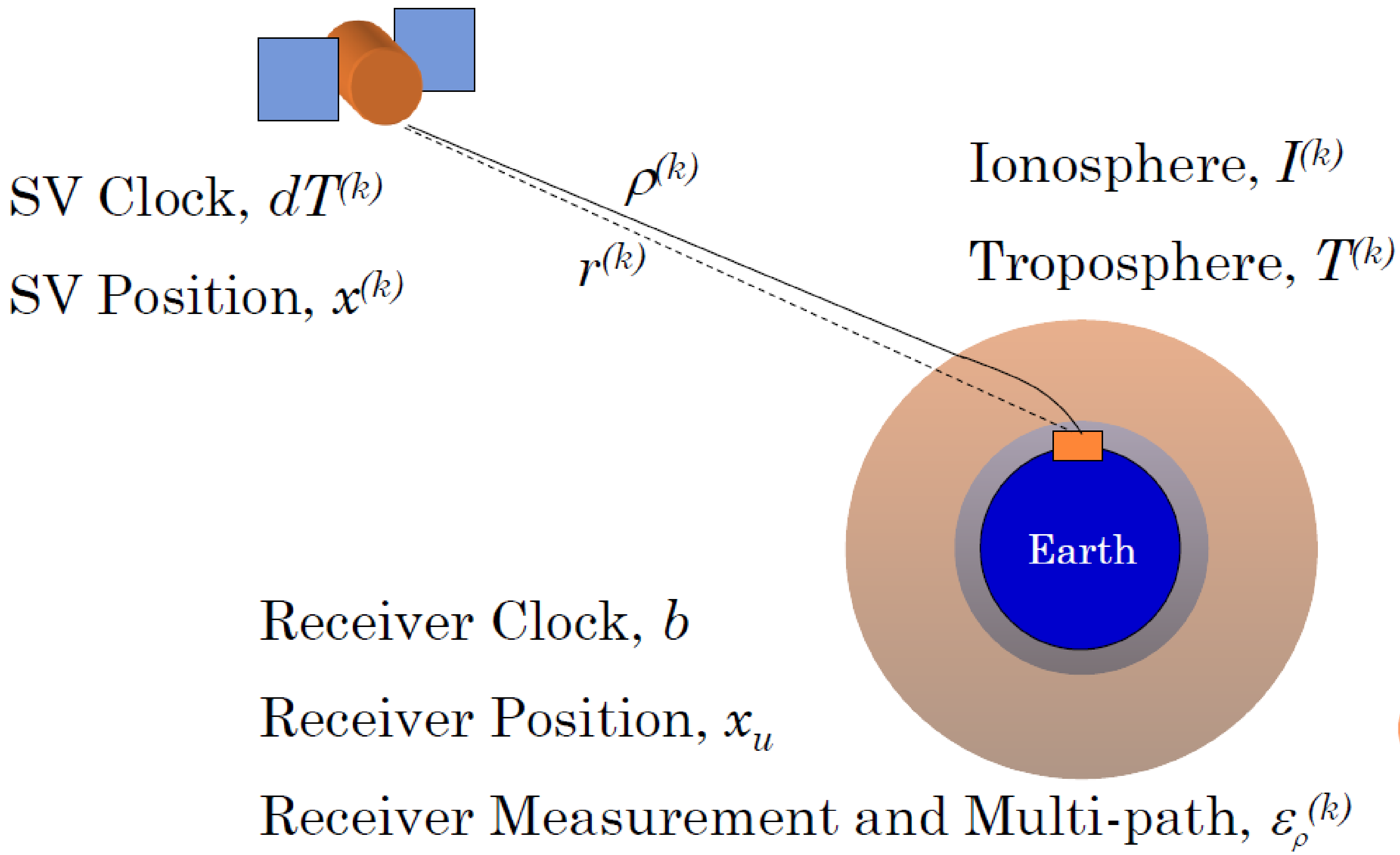
- Full



Source: Steven Waslander, ME640 2018

Position Sensors

GPS Measurements & Error Sources



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Source: Steven Waslander, ME640 2018

POSITION SENSORS

- Code Phase Position Fix Measurement Model
  - Nonlinear measurement model of pseudorange, $\rho^{(k)}$ in meters

$$\rho^{(k)} = \underbrace{||x^{(k)} - x_u||}_{\text{Range}} + \underbrace{b - c(dT^{(k)})}_{\text{Clocks}} + \underbrace{I^{(k)} + T^{(k)}}_{\text{Atmospheric}} + \underbrace{\epsilon_\rho^{(k)}}_{\text{Other}}$$

- Nonlinear least squares (NLLS) estimation used
  - Combine pseudorange measurements to form an estimate of receiver position and clock bias
- Can be augmented with motion model if known
  - Many GPS receivers include options for walking, car, aircraft etc.

Source: Steven Waslander, ME640 2018

Position Sensors

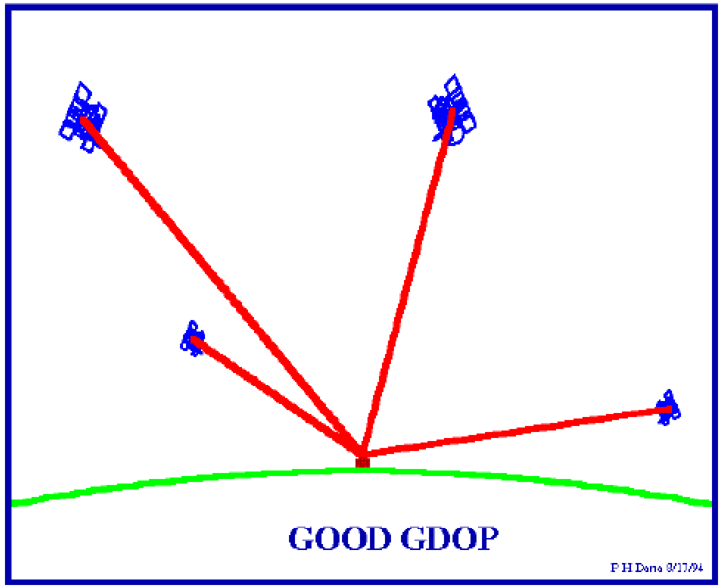
- Main GPS Error Sources
  - Geometry, independence of pseudorange measurements
  - Atmospheric delays
  - Multipath Signal Interference
- Other contributing factors
  - Satellite Position Calculation
  - Satellite Clock Corrections
  - Code Tracking Error

- Errors often cited in Circular Error Probable
  - 5m 50% CEP indicates that 50% of measurements will lie within a 5m circle about the average

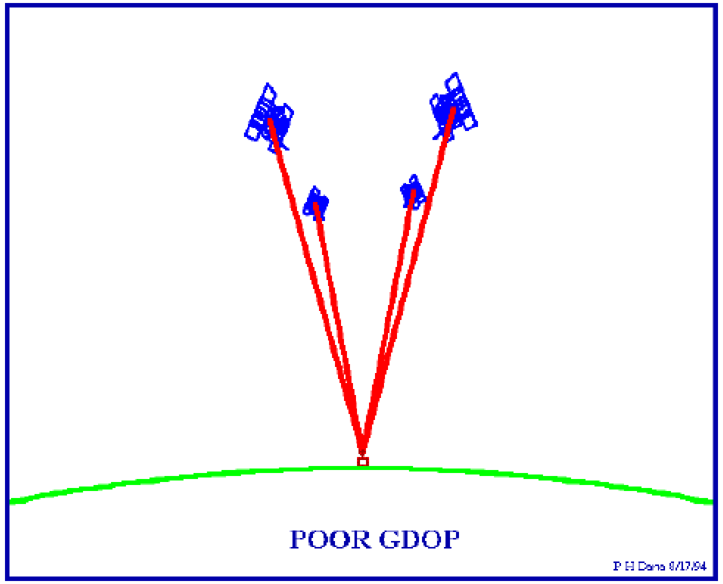
Source: Steven Waslander, ME640 2018

POSITION SENSORS

- Geometric Dilution of Precision (GDOP)
  - The lower the better
    - 1 – ideal, above 8 becomes difficult to use
  - Also available PDOP, HDOP,VDOP, TDOP



GDOP = 1.5



GDOP = 6

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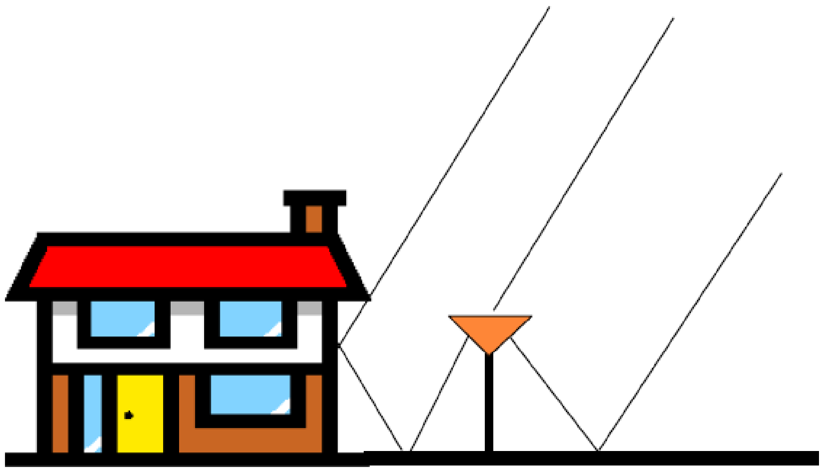
Source: Steven Waslander, ME640 2018

Position Sensors

- Multi-path errors
  - Code Error: 1-5 m
    - Weakens Correlation Spike Tracking
    - Eliminated outside of 1.5 chips (500m)
  - Ground plane essential for rejection
    - Choke ring antennas used in surveying

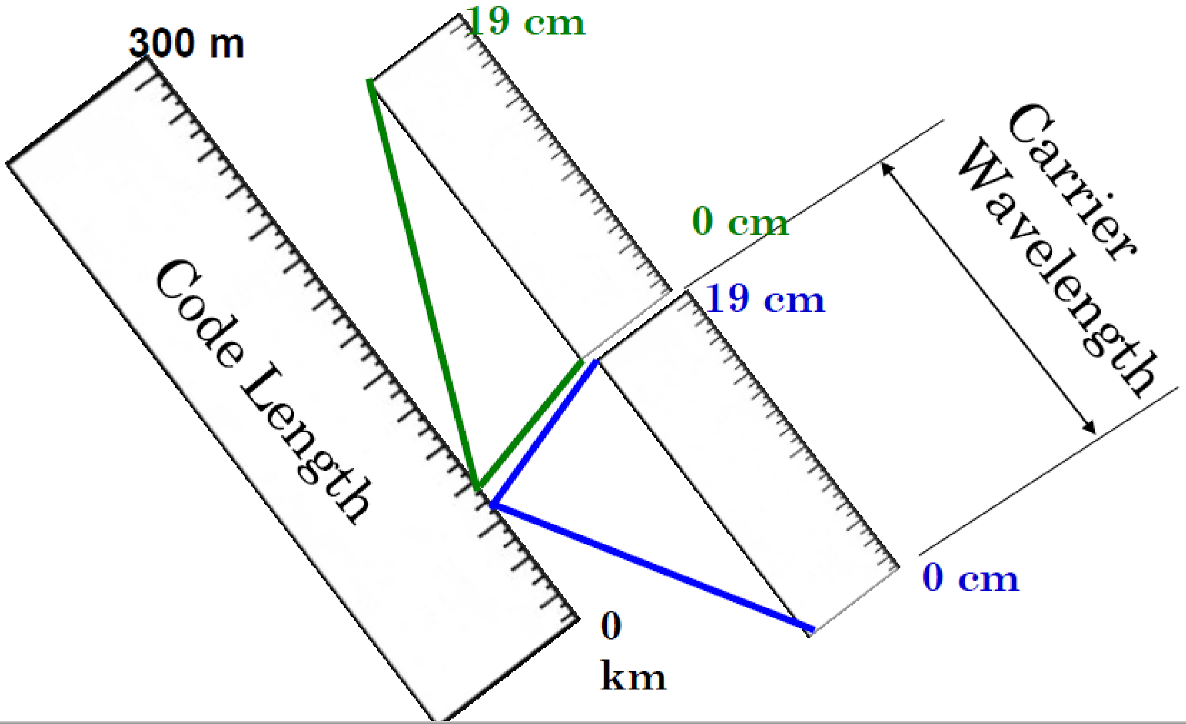
Courtesy of Trimble Navigation



Source: Steven Waslander, ME640 2018

POSITION SENSORS

- Carrier Phase Measurements
  - Its possible to track carrier phase of GPS signal along with code phase
    - e.g. Superstar II tracks to 1/1024th of a wavelength



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Source: Steven Waslander, ME640 2018

POSITION SENSORS

- Carrier Phase Measurements
  - Measurement Equation (wavelengths)

$$\phi_u^{(k)} = \lambda^{-1}\left[r_u^{(k)} - I_u^{(k)} - T_u^{(k)}\right] + f(b_u - dT^{(k)}) + N_u^{(k)} + \epsilon_{\phi,u}^{(k)}$$

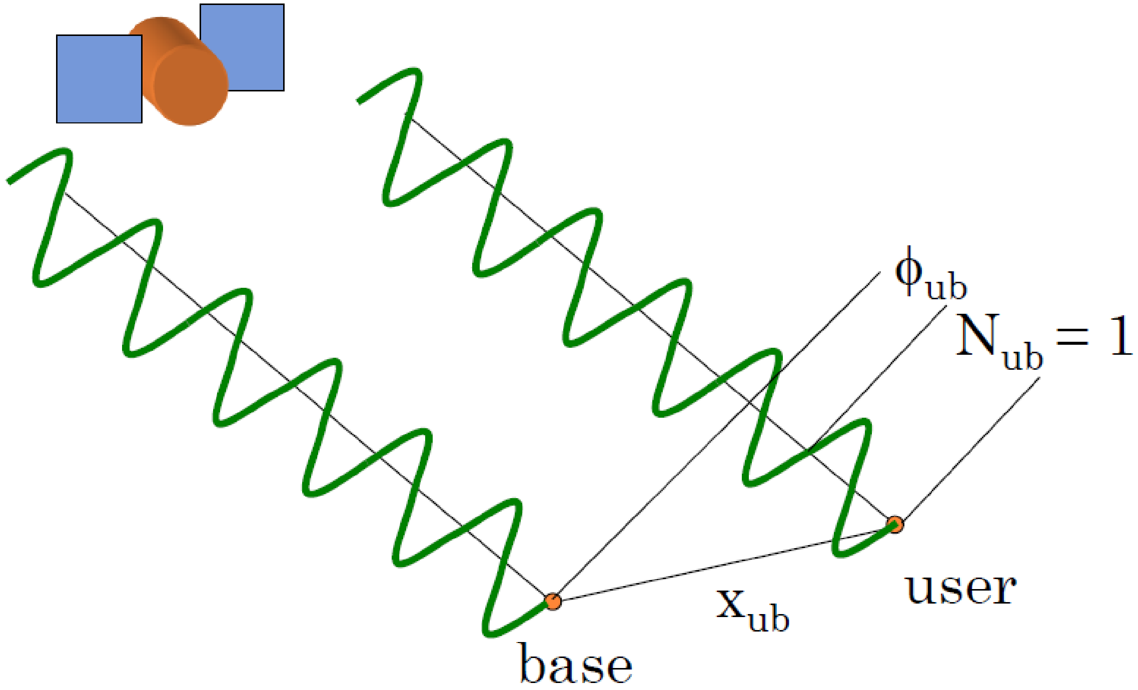
Integer Ambiguity

  - Measurement precision of mm
  - Error sources in meters
  - Integers unknown, lost in errors
  - At first glance, not very useful

Source: Steven Waslander, ME640 2018

Position Sensors

- Single Difference Geometry



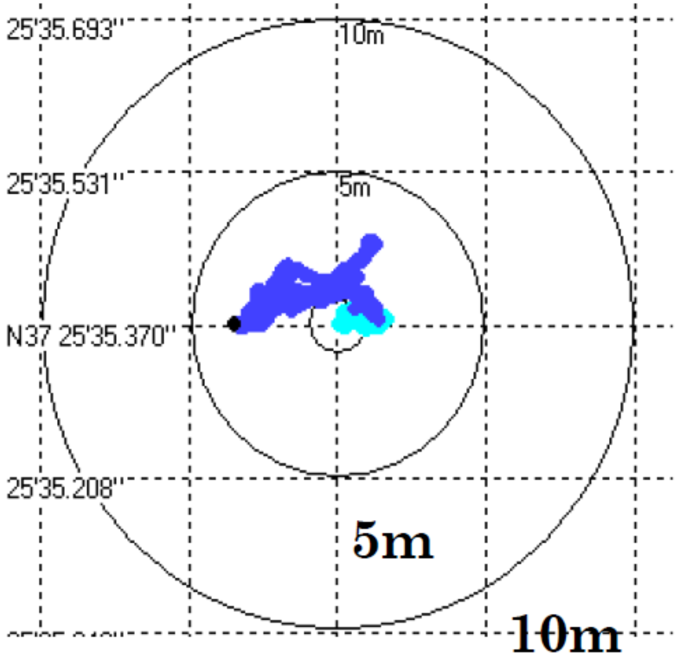
- Single Difference removes Iono, Tropo, SV Clock, but adds base clock error
- Double difference also removes base clock error
  - RTK (real time kinetic) systems use double difference

Source: Steven Waslander, ME640 2018

Carrier Phase Position Accuracy

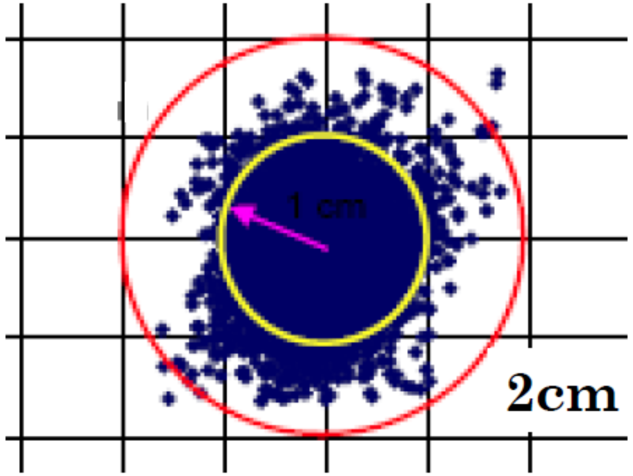
Coded Phase Solution: 25 Minutes

- Standard (3-5m CEP)
- With DGPS corrections (WAAS, PPP) (0.5 - 1.5m CEP)



Carrier Phase Solution: 24 Hours

- Double Difference Technique (1-2cm CEP)



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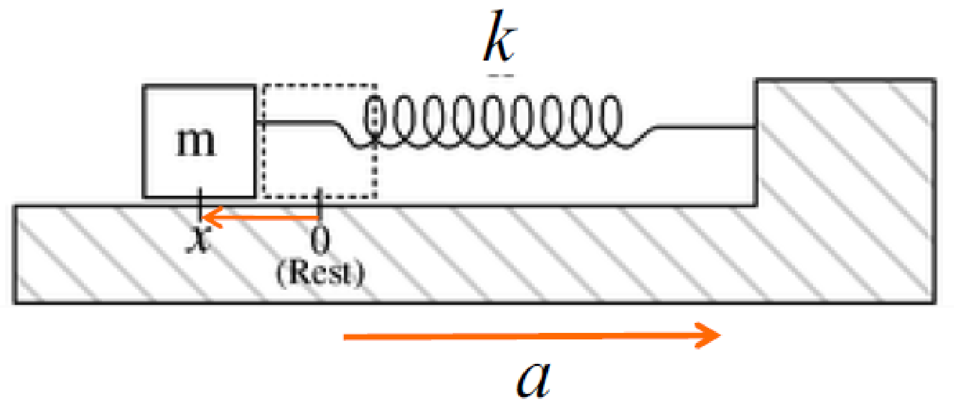
Source: Steven Waslander, ME640 2018

Inertial Sensors

- Accelerometers
  - Measure acceleration in a single direction by balancing acceleration with spring displacement.



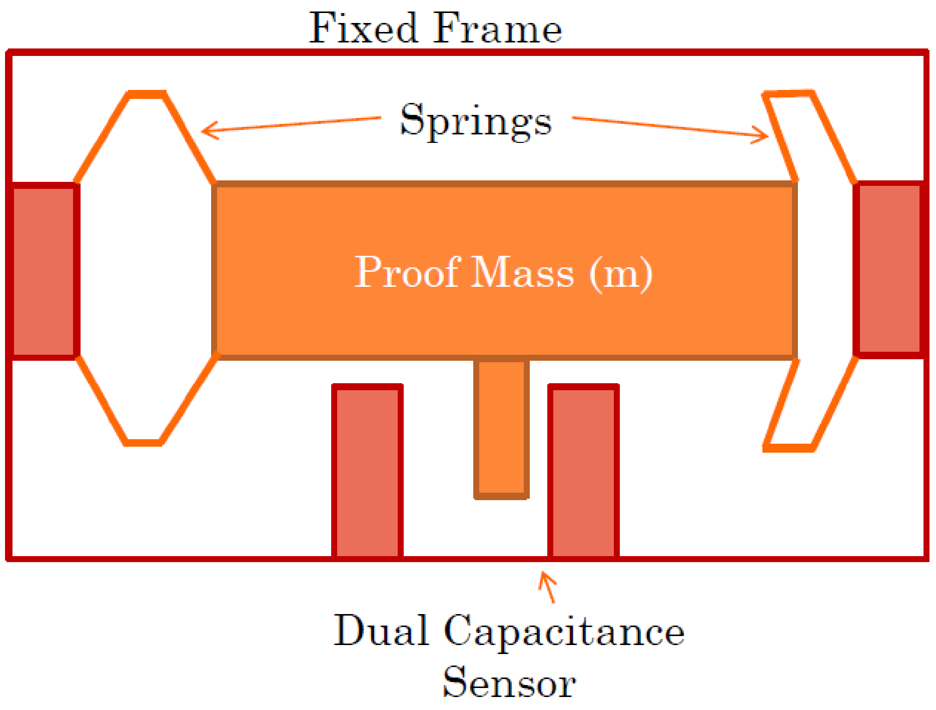
$$F = kx = ma$$

$$a = \frac{kx}{m}$$

Source: Steven Waslander, ME640 2018

Inertial Sensors

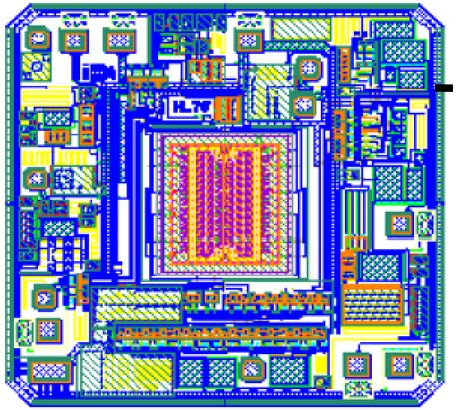
- Analog Devices MEMS Accelerometers
  - iMEMS ADXL150
    - Proof mass suspended from folded springs (0.1 μgm)
    - Capacitive position measurement (10 fF full scale)



Source: Steven Waslander, ME640 2018

Inertial Sensors

- Accelerometer issues
  - Bias
    - Any bias in measurement causes linear growth in velocity error, quadratic growth in position error
  - Vibration
    - Actual accelerations, cannot be rejected unless known in advance
  - Temperature
    - Changes the spring constant
    - Calibration essential to avoid bias
  - Shock
    - Surprisingly durable
      - 10,000 g shock tolerance

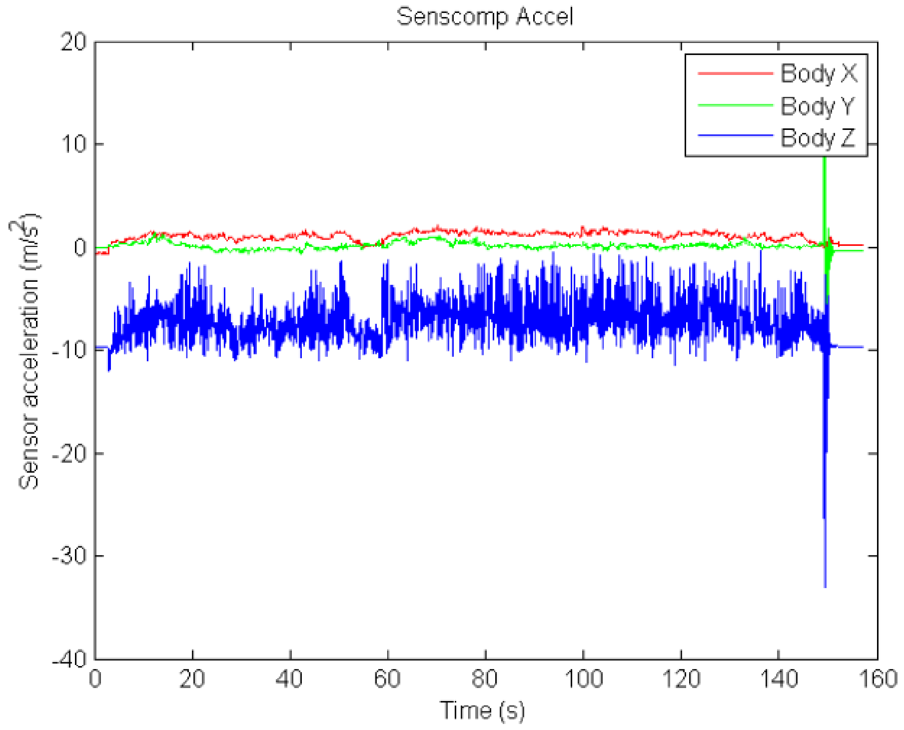


Courtesy of Analog Devices

Source: Steven Waslander, ME640 2018

Inertial Sensors

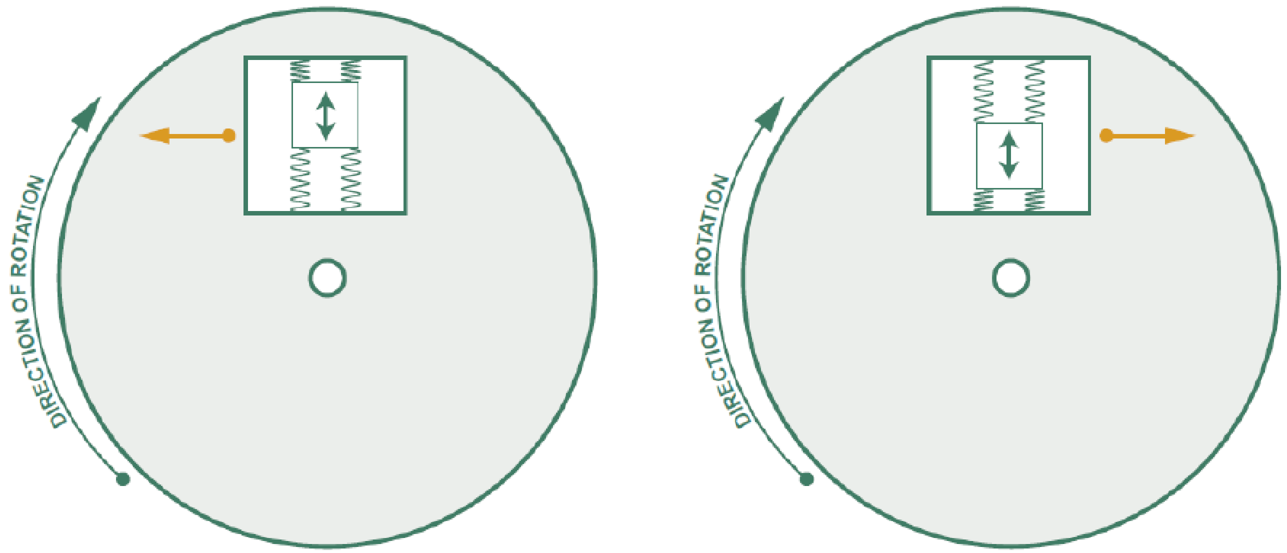
- Accelerometer Data
  - Aeryon Scout quadrotor in hover flight
    - Low pass hardware filter added to raw sensor output
    - High vibration environment, particularly in z axis



Source: Steven Waslander, ME640 2018

INERTIAL SENSORS

- Gyroscopes
  - Senses Coriolis acceleration: $a_c = 2\omega \times v_{rel}$
  - Vibrating proof mass oscillates in one direction
  - Coriolis acceleration causes perpendicular oscillation at same frequency

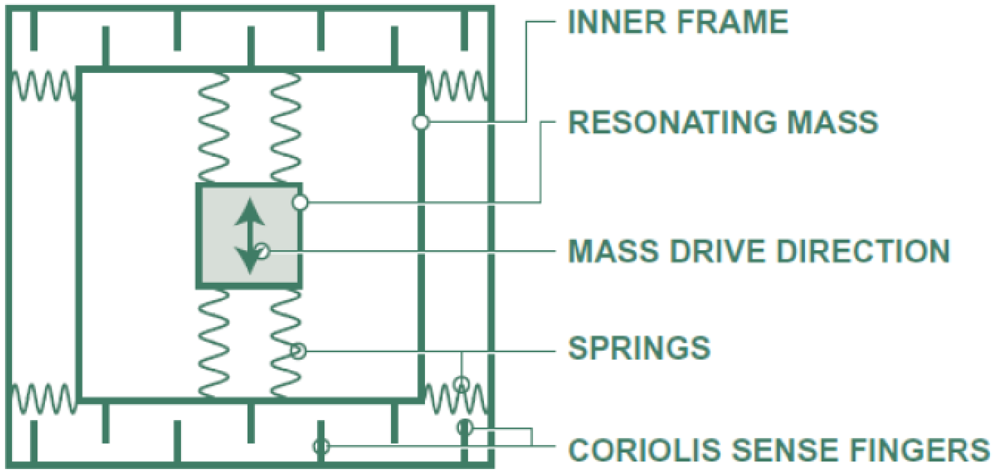


Courtesy of Analog Devices

Source: Steven Waslander, ME640 2018

Inertial Sensors

- Gyroscopes
  - Oscillating proof mass structure is suspended by four additional springs perpendicular to axis of oscillation
  - Dual capacitive measurements taken at each corner
  - Measurement signal correlated with oscillation frequency to eliminate other accelerations

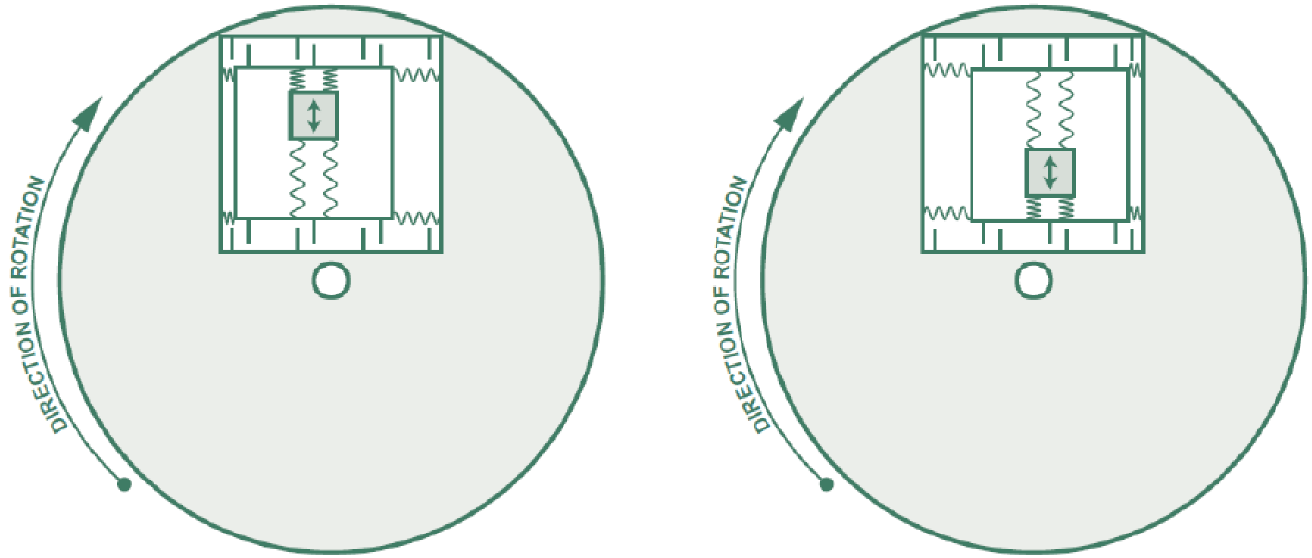


Courtesy of Analog Devices

Source: Steven Waslander, ME640 2018

Inertial Sensors

- Gyroscopes
  - As rotation occurs, mass and frame move in predictable pattern

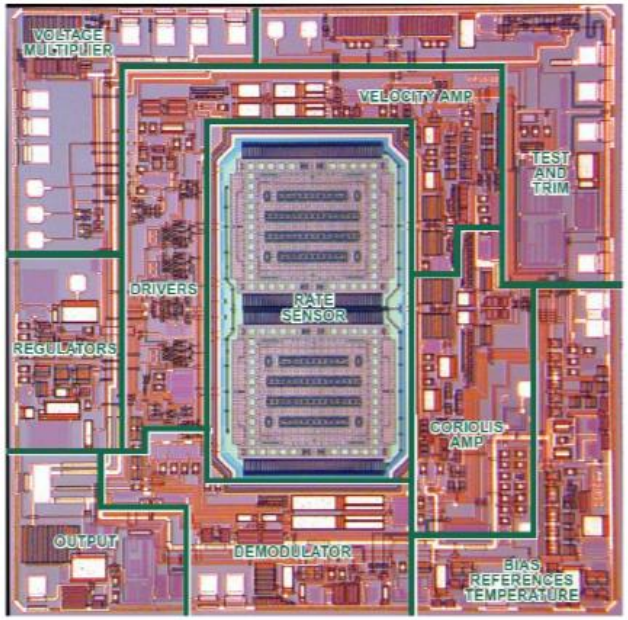


Courtesy of Analog Devices

Source: Steven Waslander, ME640 2018

INERTIAL SENSORS

- Gyroscope measurement issues
  - Vibration
    - Especially at drive frequency
    - Coning particularly troubling
    - Vibration isolation can be used
  - Temperature
    - Affects spring constant
    - Built in compensation
    - Bias estimation
  - Shock
    - Surprisingly durable (10K g)
  - Range
    - Common levels
      - 150, 300, 600, 1200 °/s
    - Turntable @ 33 1/3 rpm
      - = 200 °/s



Courtesy of Analog Devices

Source: Steven Waslander, ME640 2018

Inertial Sensors

- Magnetometers
  - 4000 year old technology
  - Use earth's magnetic field to provide inertial orientation
  - 3-axis version provides magnetic field vector
  - Good precision, poor accuracy
  - Many disadvantages
    - Earth's magnetic field is weak
    - Field easily disturbed by presence of metal, current, magnets
    - Particularly ineffective indoors (rebar!)
    - Calibration required frequently

Devantech Compass

Source: Steven Waslander, ME640 2018