

# Lecture 17, Feb 9, 2026

## Overview of Sensors – Exteroceptive Sensors

- *LiDAR* (Light Detection And Ranging) uses light pulses to measure the distance from the sensor to each point in the environment, in 2D or 3D
  - LiDARs send laser pulses using a rotating optical system, and measures the time of flight of each pulse to determine the distance
    - \* Time of flight is usually determined using phase shift of the light wave sent out, using interference
    - \* We could get more than a single return for each beam (e.g. the beam can go through snow or leaves); modern sensors will give all the returns as well as the strongest one, so we can see through some things
    - \* The returning pulse also provides an intensity, which depends on the range, surface material, and angle of incidence
    - \* Complete scans can be produced using a spinning head, rotating mirror, or other optical system (e.g. Rinsley prisms, MEMS mirrors/solid state)
  - For a 2D scanner, we get bearings of the pulses and ranges for each pulse
    - \*  $\psi^s = [-\psi_{\min}^s \quad \dots \quad \psi_{\max}^s]$
    - \*  $r^s = [r_1^s \quad \dots \quad r_J^s]; r_j^s \in [0, r_{\max}^s]$
    - \* Given a landmark in some position, we can compute the bearing and range or vice versa
  - For 3D scanners we get two angles for each pulse
    - \*  $\rho_{ij} = \sqrt{x_{ij}^2 + y_{ij}^2 + z_{ij}^2} + \Delta\rho$
    - \*  $\theta_{ij} = \tan^{-1} \left( \frac{y_{ij}}{x_{ij}} \right) + \Delta\theta$
    - \*  $\alpha_{ij} = \tan^{-1} \left( \frac{z_{ij}}{\sqrt{x_{ij}^2 + y_{ij}^2}} \right) + \Delta\alpha$
  - Early LiDAR systems needed manual calibration, but modern LiDARs come pre-calibrated and the calibration usually stays valid throughout the sensor lifetime
- *Time-of-flight* (ToF) cameras (aka *flash LiDARs*) work similarly to LiDARs but captures the entire point cloud at once
  - Range is computed using phase modulation similarly to LiDAR
  - Due to the modulation, there is typically a range ambiguity beyond  $\sim 7$  m
  - More suitable for indoor use since direct sunlight can cause issues
- *Sonic range finders* (*SODARs*) measures the time of flight of an ultrasonic pulse to determine distance to a single point
  - They are popular in underwater applications since sound travels faster and doesn't have issues with light-based sensors
  - Range is relatively limited, and the sound wave has a wide cone of spread, making them useful for free space mapping/obstacle avoidance but not precise mapping
  - The speed of sound also limits the top update rate of these sensors (i.e. the sound wave must travel the full range before the next one is sent)
- *Radar* reflects long-wavelength radio waves off objects to determine range via time of flight
  - Requires a lot of signal processing on the returned signal to get a useable image
  - Generates primarily 2D measurements in a plane
  - Becoming more popular in automotive applications using millimetre-wave radar (which measures distance and velocity, but not angle reliably)
- *Global navigation satellite systems* (GNSS) are satellites with known orbits and synchronized clocks that transmit signals to triangulate the position of the receiver
  - To solve for the position, we need 4 satellites for the 3 position DoFs and a receiver clock offset
  - GPS uses a base carrier signal at 1575 MHz, which is modulated into a code at 1.023 MHz; this code is then further modulated to transmit the actual navigation data (including satellite orbit

- corrects etc.) at 50 bps
- \* The code uses a set pattern (32 unique *gold codes*), which are very distinct and easy to match
  - The path the signal takes from the satellite to the receiver is curved, resulting in the *pseudorange*
    - \* Nonlinear least squares is used to solve for receiver position and clock bias from pseudorange measurements
    - \* The more satellites, the more accurate our estimates; most modern receivers are multi-system
    - \* Can be augmented with a motion model if known
  - Many sources of error can occur:
    - \* Satellite geometry is one of the most important factors (*dilution of precision*)
      - The more distributed the satellites, the more precision we get; if satellites are bunched up, pseudoranges from different satellites won't be independent
    - \* Ionospheric and tropospheric errors due to humidity
    - \* *Multi-path* effects can occur where signals bounce off other objects before getting received
  - Errors are often measured in *circular error probable* (CEP), e.g. 5 m 50% CEP means 50% of measurements will lie within a 5 m circle of the average
  - With plain GPS, we can get  $\sim 10$  m accuracy since atmospheric effects cause inaccuracies
  - With differential GPS (DGPS), a base station with known location is used, errors from atmospheric effects can be corrected, resulting in  $< 10$  cm of accuracy
    - \* This is known as single difference and eliminates atmospheric errors and satellite clock errors, since both the base station and rover receive the same signal
    - \* However this adds a base clock error which requires an additional satellite to solve for
  - With RTK GPS, a base station is used along with the phase of the carrier signal to get  $\sim 2$  cm of accuracy relative to the base station
    - \* RTK GPS uses double difference, which uses the difference between single differences to also eliminate base clock error
      - In theory we can keep taking higher differences, but this compounds the receiver measurement errors and becomes impractical fast

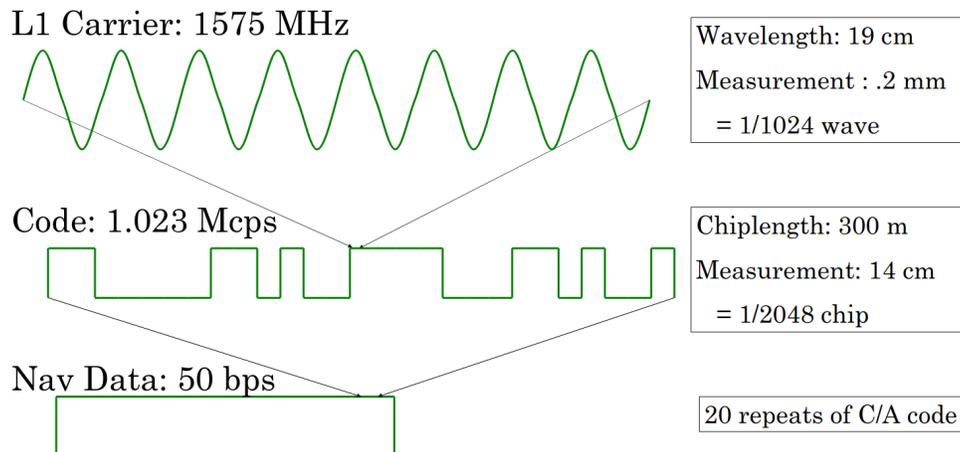


Figure 1: GPS carrier signal.