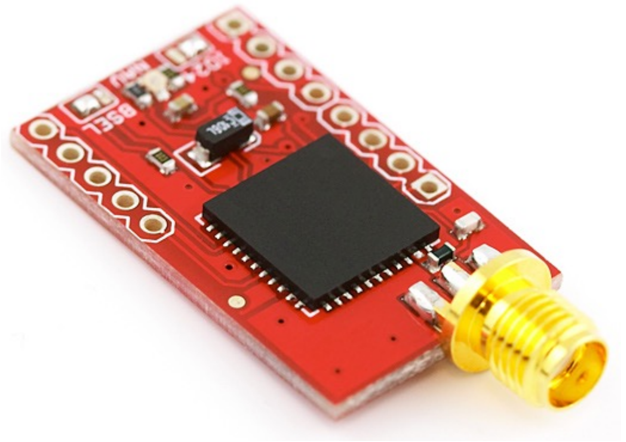
Introduction to Electrical and Computer Engineering

Signals and Timing

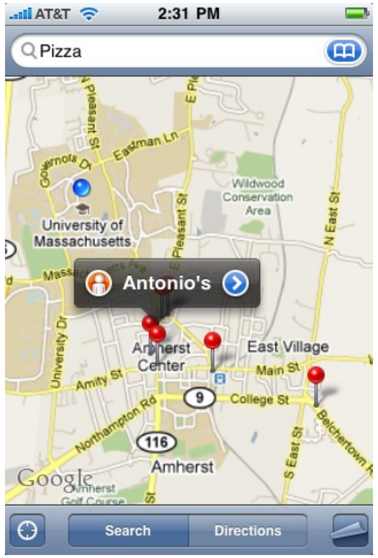
Global Positioning System Overview

- Many systems require position information
- This module:
  - Navigation
    - Errors
  - Determining position
    - Importance of time
  - Global Positioning System (GPS)
    - Principles
    - Implementation
  - Beamforming
    - Using propagation delay for other applications
    - Ultrasound medical imaging



Location-Based Systems

- Many systems require position information
- Navigation
  - Car: Location (2D) + maps + routing
  - Plane: Location (3D), …
  - Military: Troop movement, missile/drone guidance, …
- Emergency response
  - Locate and navigate to emergency sites
- Surveying
  - Determine property boundaries
- Precision agriculture
  - Track yield, adjust fertilization
- Location-based information service



Historic Navigation Problem 1/3

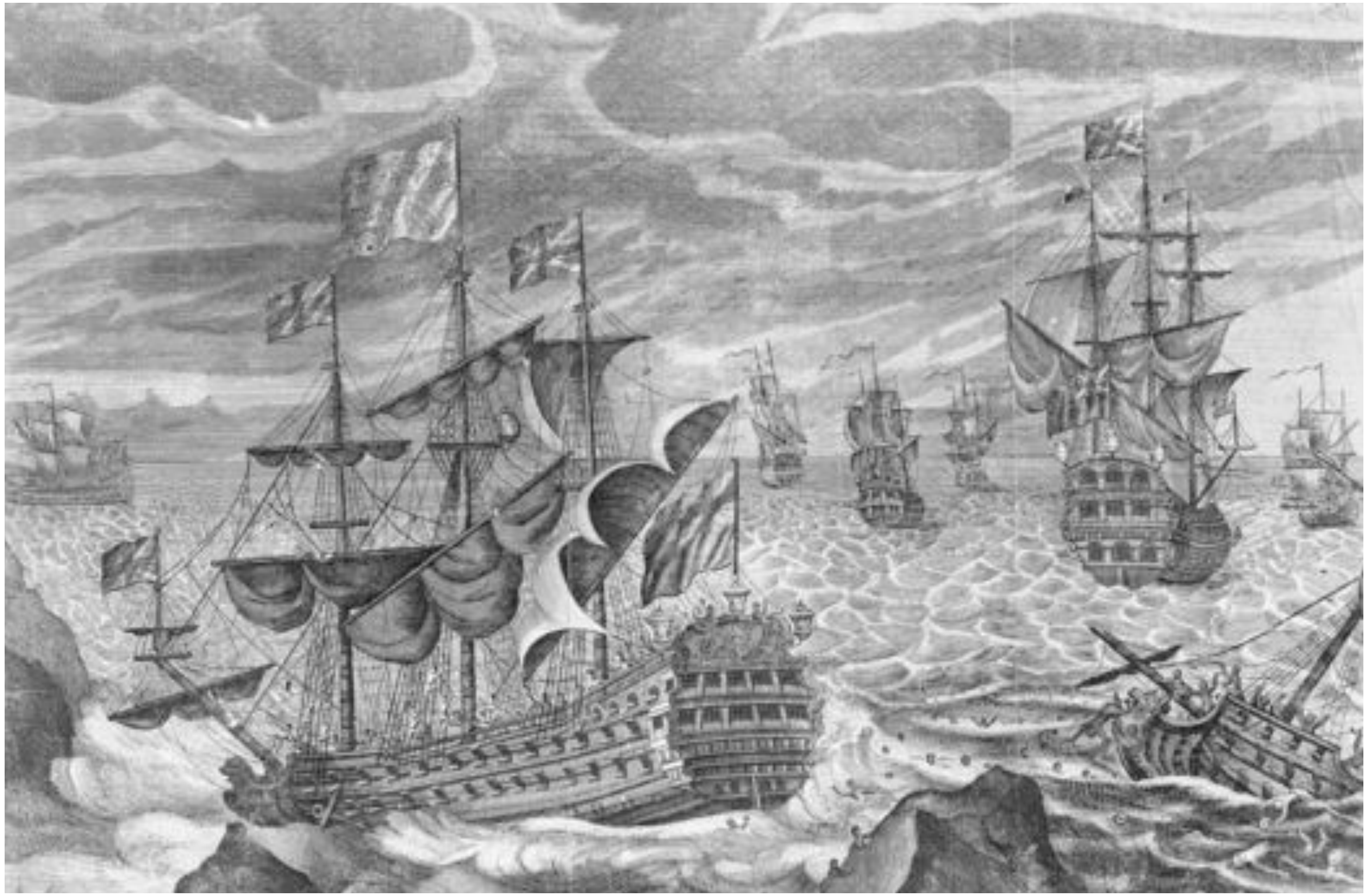
- Maps were not very accurate ("terra incognita" and "here be dragons")
  - Navigation difficult even with good maps

Historic Navigation Problem 2/3

- How would you navigate on open ocean?
  - Example: sea voyage from Plymouth, UK to Plymouth, MA?
  - What are navigation challenges when crossing ocean?

Historic Navigation Problem 3/3

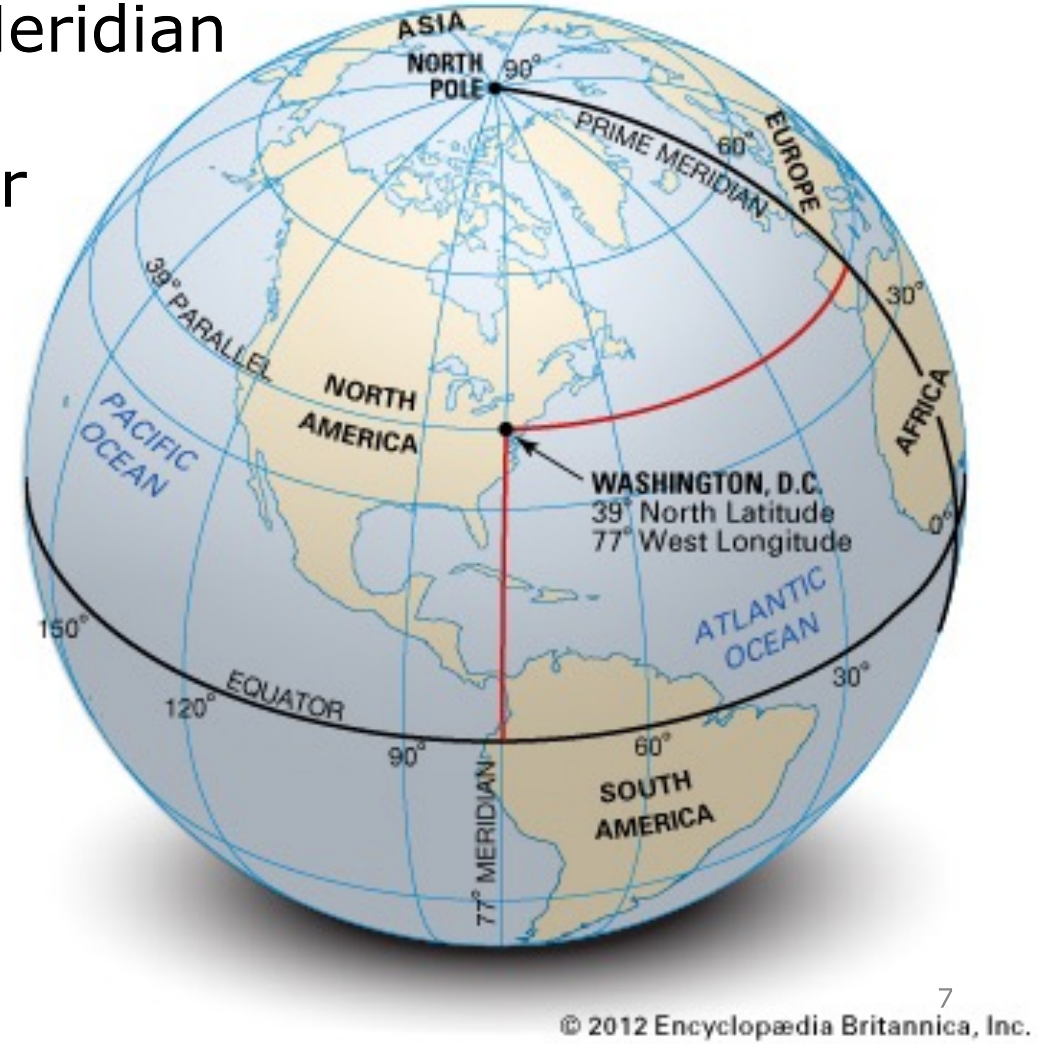
- Determining position on open ocean very difficult
  - Scilly naval disaster in 1707
    - Loss of four British warships and 1,550 sailors
  - Reason for disaster was navigation error
    - Actual position was 200 miles off



from wikipedia.com

Location / Position

- Position stated in geographic coordinate system
  - Longitude: angular distance to Prime Meridian
    - Greenwich, UK is 0°
  - Latitude: angular distance from equator
- How can latitude be determined?
- How can longitude be determined?
- Terminology:
  - Location = position in this module

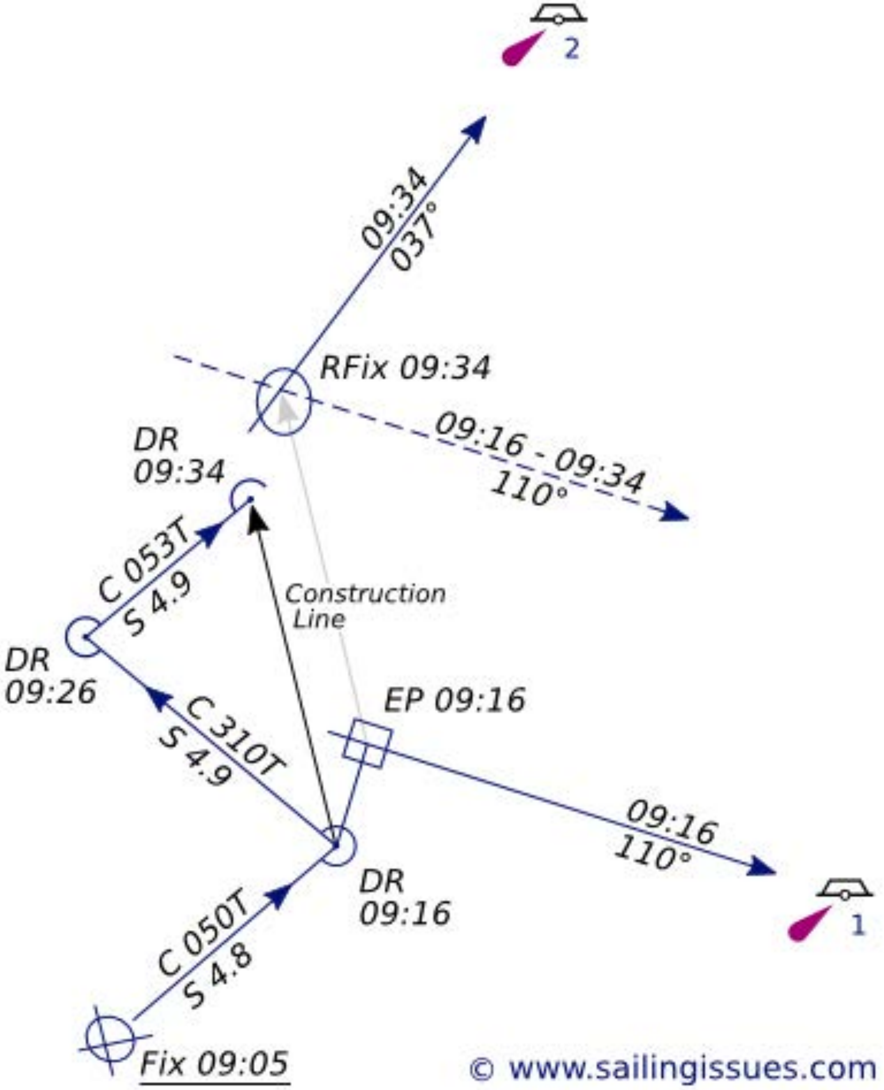


Determining Position

- Two fundamentally different approaches
  - Relative positioning
    - Determine position relative to previously known location
  - Absolute positioning
    - Determine longitude and latitude directly
- Absolute positioning difficult on open ocean
  - Limited reference points
- Why is this important to ECE?
  - Similar problem when building autonomous robots
  - Limited reference points due to limited sensor input

Relative Positioning 1/2

- “Dead Reckoning”
  - Start at known position
  - Keep track of all movements
    - Heading (from compass)
    - Distance (from speed and time)



Relative Positioning 2/2

- Example: Crossing the Atlantic

from wikipedia.com

Exercise: Dead Reckoning Robot 1/6

- Robot “ship” uses embedded system to drive wheels
  - We use program to control how far it goes
- Goal: arrive safely in Plymouth, MA
  - Correct distance: everything good
  - Too short: lost at sea
  - Too far: crash into the coastline
- Navigation
  - Determine distance of travel
  - Determine travel speed
  - Determine travel time
  - Program robot to go for that time

Exercise: Dead Reckoning Robot 2/6

- Measure distance from Plymouth, UK to Plymouth, MA (in inches)
  - Measurement 1:
  - Measurement 2:
  - Measurement 3:
- Distance used:

Exercise: Dead Reckoning Robot 3/6

- Move robot for 1 second to determine speed

- How to limit running time?

Exercise: Dead Reckoning Robot 4/6

- Measure speed: distance covered in 1 second
  - Measurement 1:
  - Measurement 2:
  - Measurement 3:
- How long should robot drive to cross ocean?

Exercise: Dead Reckoning Robot 5/6

- Set running time to covered entire distance
  - Example here: 12.3 seconds

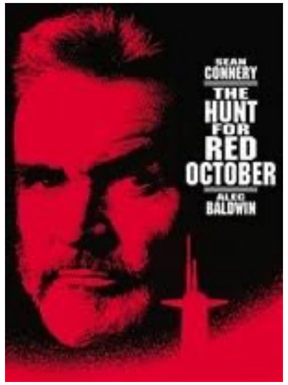
Exercise: Dead Reckoning Robot 6/6

- Assessment of our ocean crossing
  - What worked well?
  - What didn’t work well?
  - What are potential improvements?

Dead Reckoning

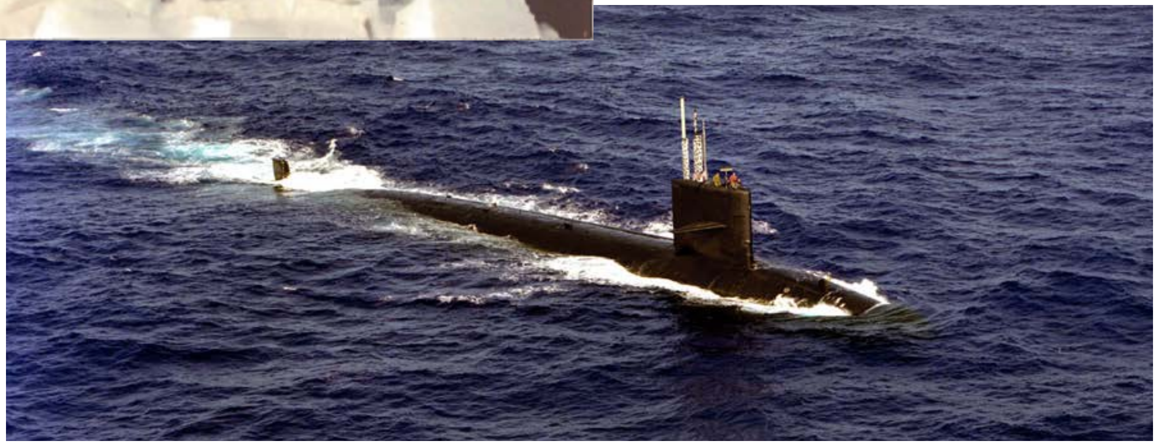
- Navigation by direction/speed/time
  - No absolute reference

Scene from
“The Hunt for
Red October”



Side Note

- Dean of the College of Engineering: Prof. Sanjay Raman
  - Served on USS Seahorse (SSN-669) Sturgeon class nuclear sub



Measurement Variation

- Why do measurements vary for our example?

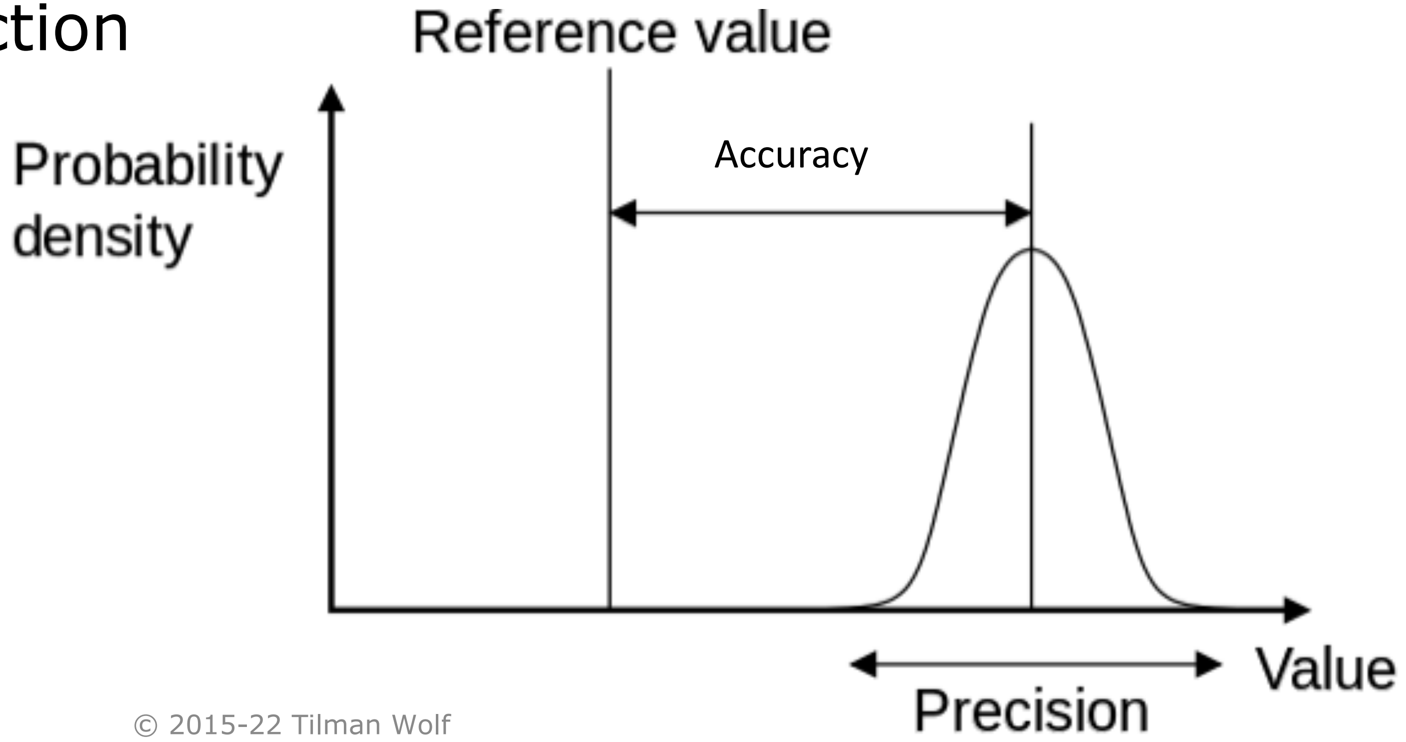
- What happens when variations “add up”?

Measurements and Errors

- Assessment of measurements
  - Accuracy ("trueness"): How close is result to true value?
  - Precision: How close are repeated measurements to each other?
- Measurement often modeled as Normal distribution
  - Probability density function

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

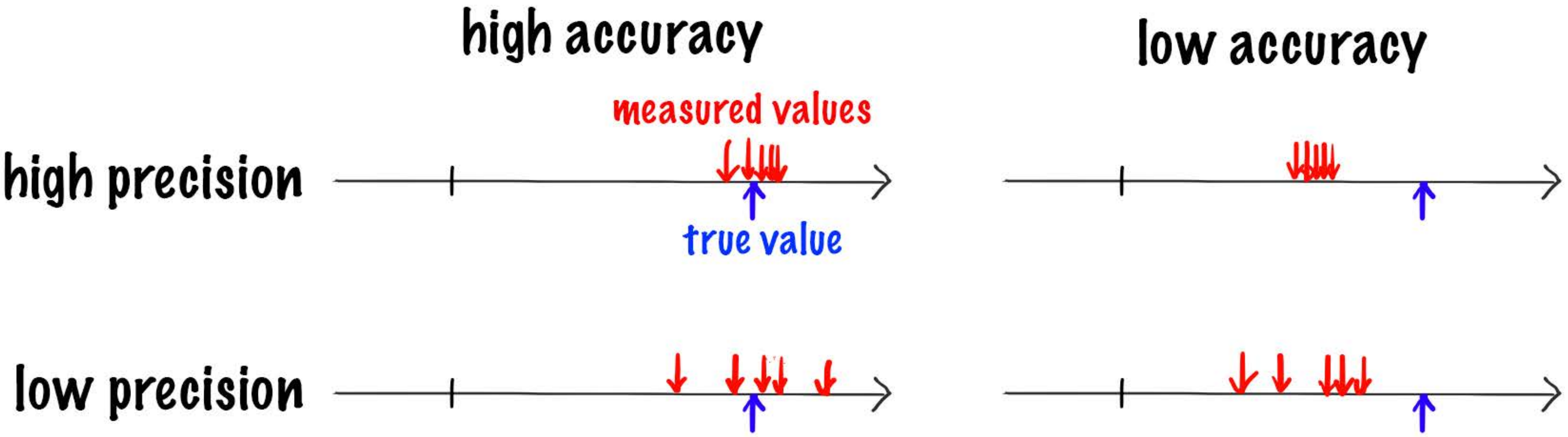
    - Mean μ
    - Standard deviation σ



from wikipedia.com

Accuracy and Precision

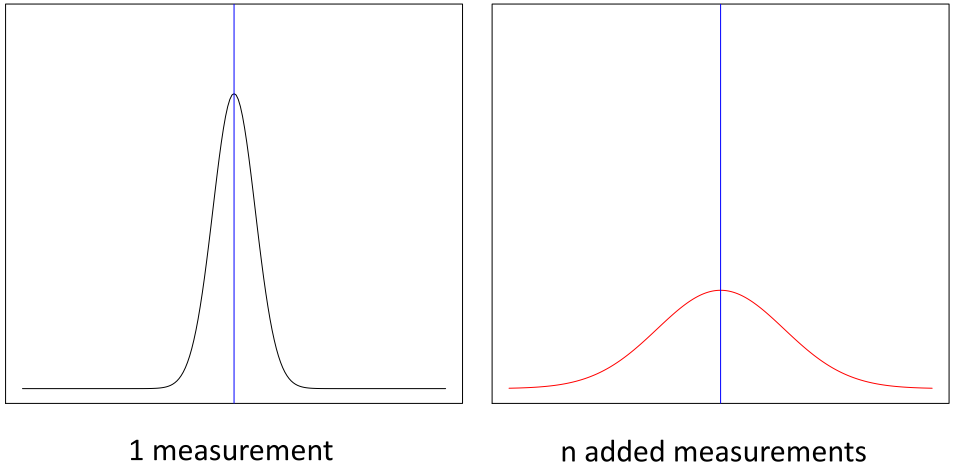
- For each example:
  - Accuracy: high or low?
  - Precision: high or low?



Addition of Errors 1/2

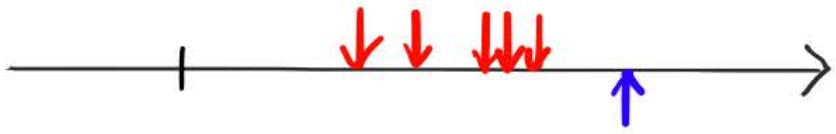
- Errors
  - Random: inherent fluctuations in readings
  - Systematic: imperfect calibration / readings
- The good case: errors are independent
  - High accuracy, low precision

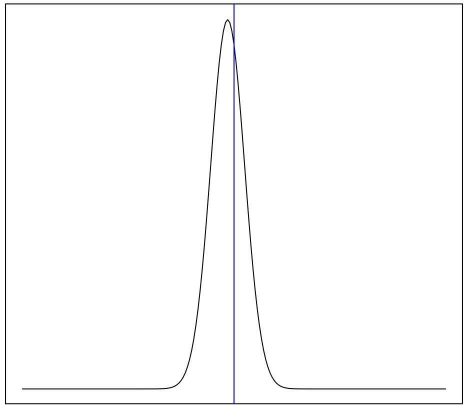
- Addition of repeated measurements
  - Average (or mean):
    - Individual measurements are accurate (on average)
    - Variation in one direction is cancelled by variation in other direction
    - Mean of sum is accurate
  - Precision:
    - Overall precision flattens out a bit



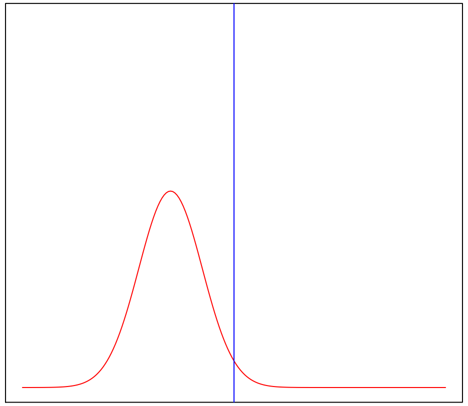
Addition of Errors 2/2

- The bad case: errors are systematic
  - Low accuracy
  - High precision
- Addition of repeated measurements
  - Average (or mean):
    - Errors of individual measurements add up
    - Variation in one direction is **not** cancelled by variation in other direction
    - Mean of sum gets less accurate
  - Precision:
    - Overall precision remains high
- Dead reckoning difficult as systematic errors add up





1 measurement



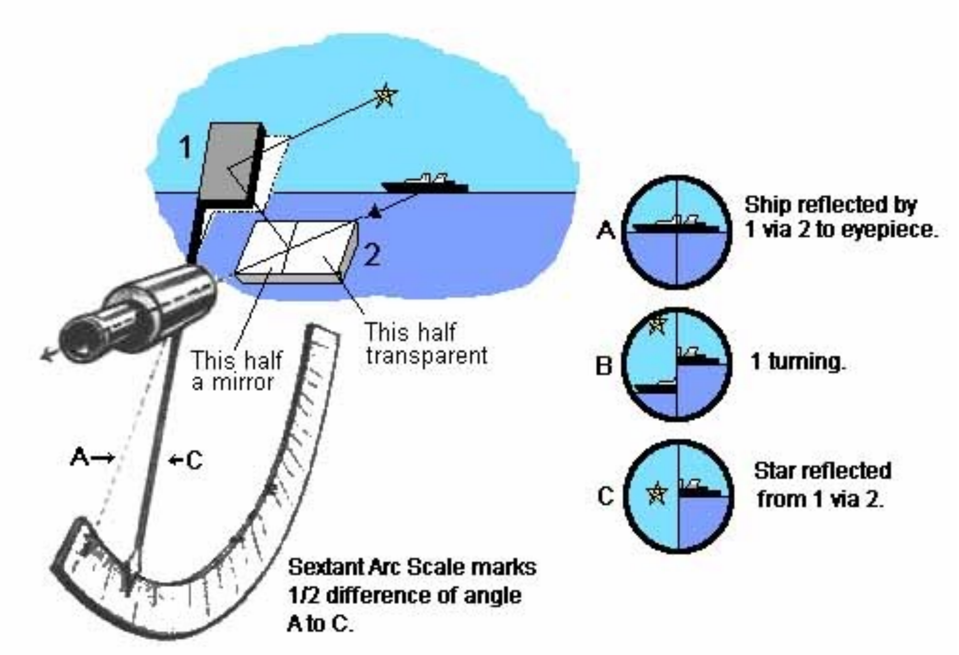
n added measurements

Absolute Position

- How can latitude be determined independently?
- How can longitude be determined independently?
- No use of prior references
  - “Absolute” position
- Uses astronomical references

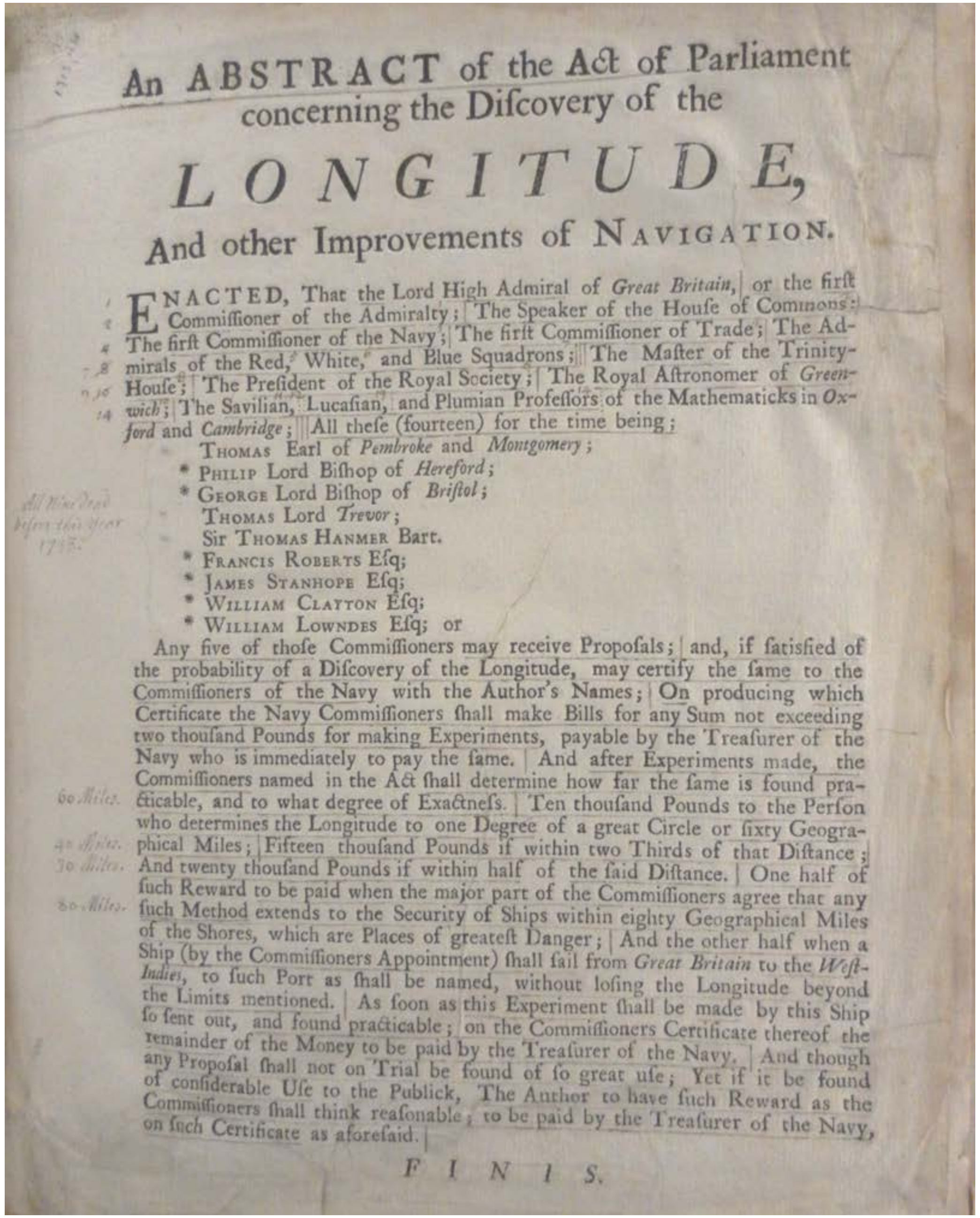
Latitude

- Latitude affects position of sky over observer
  - Sun's position
  - Stars' positions
- Sextant to measure angle against horizon



Longitude

- "Grand challenge" to spur innovation
- British government offered £20,000 in 1714
  - Accuracy within 30 nautical miles (½ degree)
- How can we determine longitude?



An ABSTRACT of the Act of Parliament concerning the Diſcovery of the

LONGITUDE,

And other Improvements of NAVIGATION.

ENACTED, That the Lord High Admiral of *Great Britain*, or the firſt Commiſſioner of the Admiralty; The Speaker of the Houſe of Commons: The firſt Commiſſioner of the Navy; The firſt Commiſſioner of Trade; The Admirals of the Red, White, and Blue Squadrons; The Maſter of the Trinity-Houſe; The Preſident of the Royal Society; The Royal Aſtronomer of *Greenwich*; The Savilian, Lucaſian, and Plumian Profeſſors of the Mathematicks in *Oxford* and *Cambridge*; All theſe (fourteen) for the time being;

THOMAS Earl of *Pembroke* and *Montgomery*;
* PHILIP Lord Biſhop of *Hereford*;
* GEORGE Lord Biſhop of *Briſtol*;
THOMAS Lord *Trevor*;
Sir THOMAS HANMER Bart.
* FRANCIS ROBERTS Eſq;
* JAMES STANHOPE Eſq;
* WILLIAM CLAYTON Eſq;
* WILLIAM LOWNDES Eſq; or

Any five of thoſe Commiſſioners may receive Propoſals; and, if ſatisfied of the probability of a Diſcovery of the Longitude, may certify the ſame to the Commiſſioners of the Navy with the Author's Names; On producing which Certificate the Navy Commiſſioners ſhall make Bills for any Sum not exceeding two thouſand Pounds for making Experiments, payable by the Treaſurer of the Navy who is immediately to pay the ſame. And after Experiments made, the Commiſſioners named in the Act ſhall determine how far the ſame is found practicable, and to what degree of Exactneſs. Ten thouſand Pounds to the Perſon who determines the Longitude to one Degree of a great Circle or ſixty Geographical Miles; Fifteen thouſand Pounds if within two Thirds of that Diſtance; And twenty thouſand Pounds if within half of the ſaid Diſtance. One half of ſuch Reward to be paid when the major part of the Commiſſioners agree that any ſuch Method extends to the Security of Ships within eighty Geographical Miles of the Shores, which are Places of greateſt Danger; And the other half when a Ship (by the Commiſſioners Appointment) ſhall ſail from *Great Britain* to the *Weſt-Indies*, to ſuch Port as ſhall be named, without loſing the Longitude beyond the Limits mentioned. As ſoon as this Experiment ſhall be made by this Ship ſo ſent out, and found practicable; on the Commiſſioners Certificate thereof the remainder of the Money to be paid by the Treaſurer of the Navy. And though any Propoſal ſhall not on Trial be found of ſo great uſe; Yet if it be found of conſiderable Uſe to the Publick, The Author to have ſuch Reward as the Commiſſioners ſhall think reaſonable; to be paid by the Treaſurer of the Navy, on ſuch Certificate as aforeſaid.

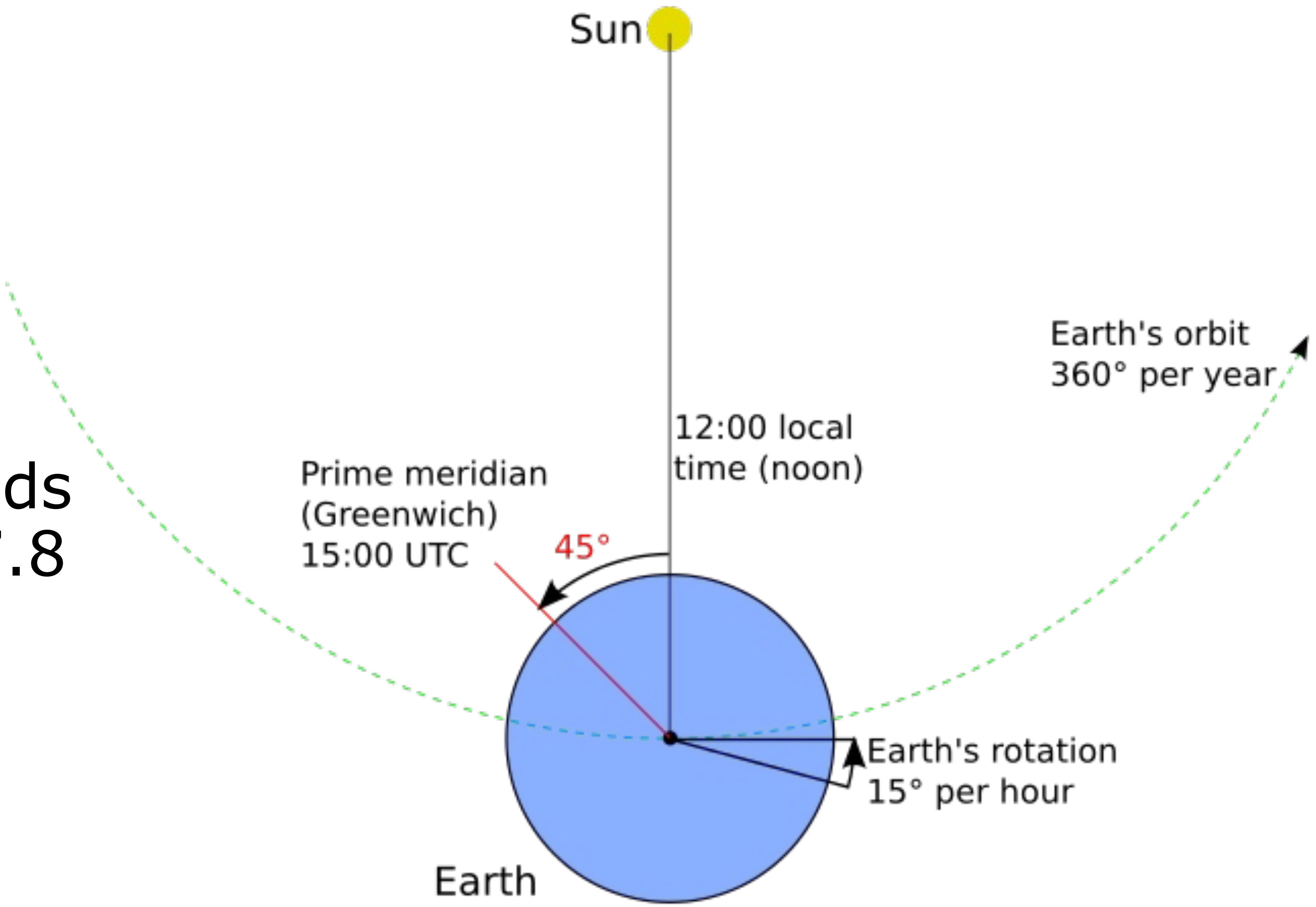
F I N I S.

Activity: Longitude Challenge

- What technique would you use for determining longitude?
- What tools would you need?

Longitude by Time 1/3

- Time is key to longitude
  - Sun moves 15° per hour (¼ degree per minute)
  - Local noon can be observed
- Circumference of earth at equator: ~40,000 km
  - ¼ degree rotation corresponds to 40,000 km / 360 / 4 = 27.8 km
- Keeping accurate time is important



Longitude by Time 2/3

- Example:
  - Home port: Plymouth, UK
    - Longitude: 4.14° W
    - Watch is set to home port (astronomical) time
  - Current location:
    - Local noon observed when watch reads 2:27 p.m.
  - What is current longitude?

Longitude by Time 3/3

- Example:
  - Home port: Plymouth, UK
    - Longitude: 4.14° W
    - Watch is set to home port (astronomical) time
  - Current location:
    - Local noon observed when watch reads 2:27 p.m.
  - What is current longitude?
- Answer:
  - Time difference between home port noon and local noon
    - 2:27 p.m. – 12:00 p.m. = 2 hours and 27 minutes
  - Sun moves 15 degrees per hour
    - 2:27 hours corresponds to 2 27/60 * 15 = 36.75 degrees
  - Since local noon is later than home port noon, we are west
  - Current longitude
    - 4.14° W + 36.75° = 40.89° W

Techniques for Keeping Time 1/2

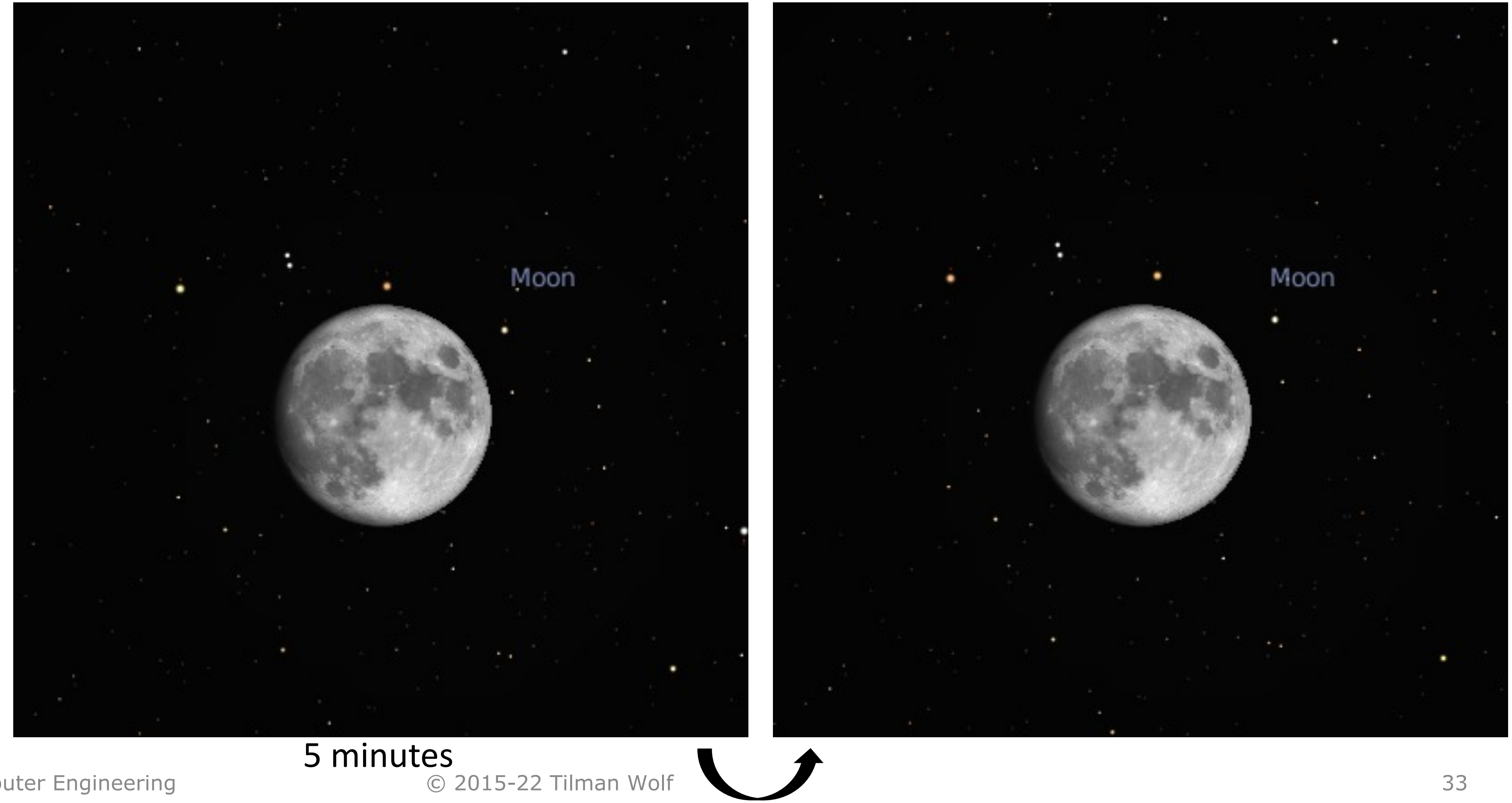
- Keeping accurate time is important
- How can you keep time?

Techniques for Keeping Time 2/2

- Keeping accurate time is important
- How can you keep time?
  - Astronomical clocks: sundial, lunar distance method
  - Mechanical clocks: spring-driven, pendulum
  - Electromechanical clocks: electric power for winding
  - Electric clocks: electric power to drive motor
  - Electronic clock: quartz crystal
  - Atomic clock: microwave signal emitted from atoms
- Two methods pursued for longitude problem
  - Lunar distance method (astronomical clock)
  - Marine chronometer (mechanical clock)

Lunar Distance Method

- Position of Moon relative to background stars
  - Prediction of Moon's path was difficult at the time



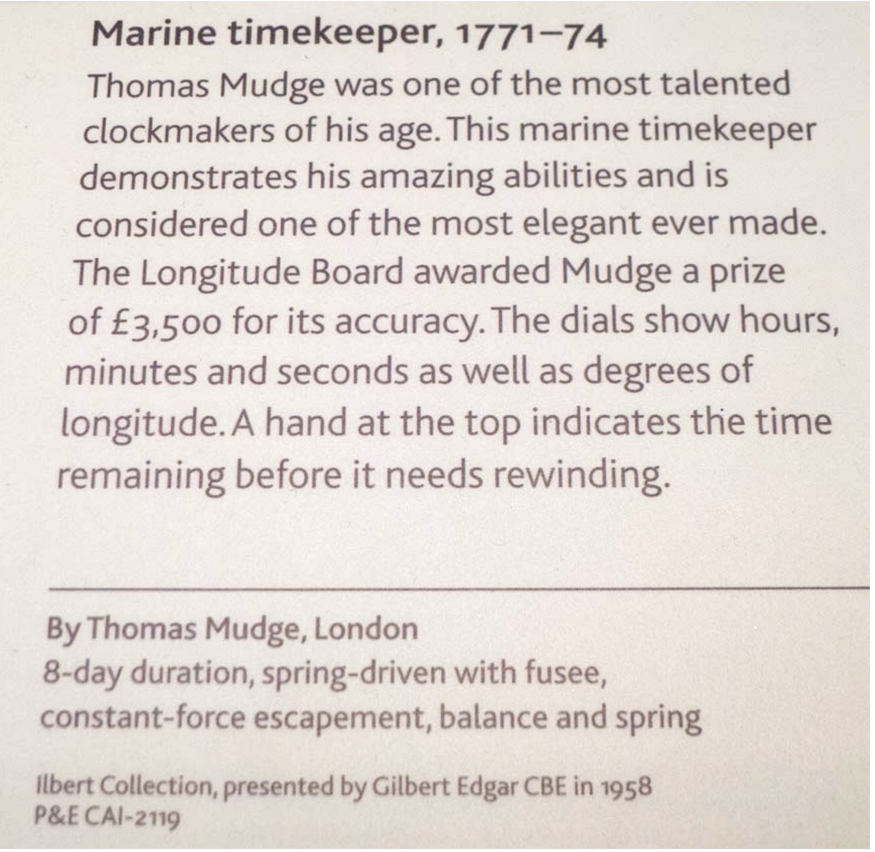
5 minutes

Marine Chronometer 1/2

- John Harrison's chronometers
  - Compen-sate for ship's movement, environ-mental conditions

Marine Chronometer 2/2

- Thomas Mudge’s chronometers
  - Improved on Harrison’s design



Marine timekeeper, 1771–74

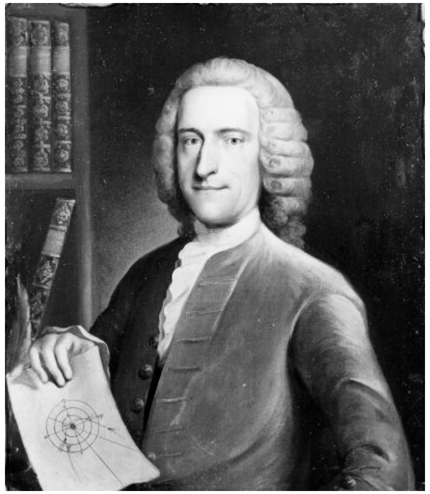
Thomas Mudge was one of the most talented clockmakers of his age. This marine timekeeper demonstrates his amazing abilities and is considered one of the most elegant ever made. The Longitude Board awarded Mudge a prize of £3,500 for its accuracy. The dials show hours, minutes and seconds as well as degrees of longitude. A hand at the top indicates the time remaining before it needs rewinding.

By Thomas Mudge, London
8-day duration, spring-driven with fusee, constant-force escapement, balance and spring

Ilbert Collection, presented by Gilbert Edgar CBE in 1958
P&E CAI-2119

Other Approaches

- William Whiston
- Solution I (with Humphrey Ditton)
  - Rockets from known location
  - Difference between light and sound determines distance
  - Allows for trilateration
- Solution II
  - Geomagnetic inclination as unique characteristic
  - Developed inclination map
- Many others



And the winners are…

Significant recipients

[edit]

Many persons benefited from the awards offered by the Board. In total, over £100,000 was given in the form of encouragements and awards. Significant among these are:[3][4]

Name	Amount	Reason
John Harrison	£14,315	Received in several payments. £4,315 was awarded during his work on his chronometers from 1737 to 1764 with the remaining £10,000 provided in 1765.
Tobias Mayer	£3,000	Contributions to the lunar distance method. His widow received the money due to Mayer's untimely death.
Thomas Mudge	£3,000	Construction of chronometers with improvements to Harrison's designs.
John Arnold	£3,000	Design and improvements to chronometers.
Thomas Earnshaw	£3,000	Design and improvements to chronometers.
Charles Mason	£1,317	Various contributions and improvements on Mayer's lunar tables.
Jesse Ramsden	£615	Design and construction of a superior dividing engine (£300) and publishing the design (£315).
Larcum Kendall	£500	Construction of a copy of Harrison's *H-4*.
Leonhard Euler	£300	Contributions to the lunar distance method in aid of Mayer.
Nathaniel Davies	£300	Design of a Lunars telescope for Mayer

Harrison also received £8,750 from Parliament in thanks for his work, bringing his total lifetime award to £23,065.

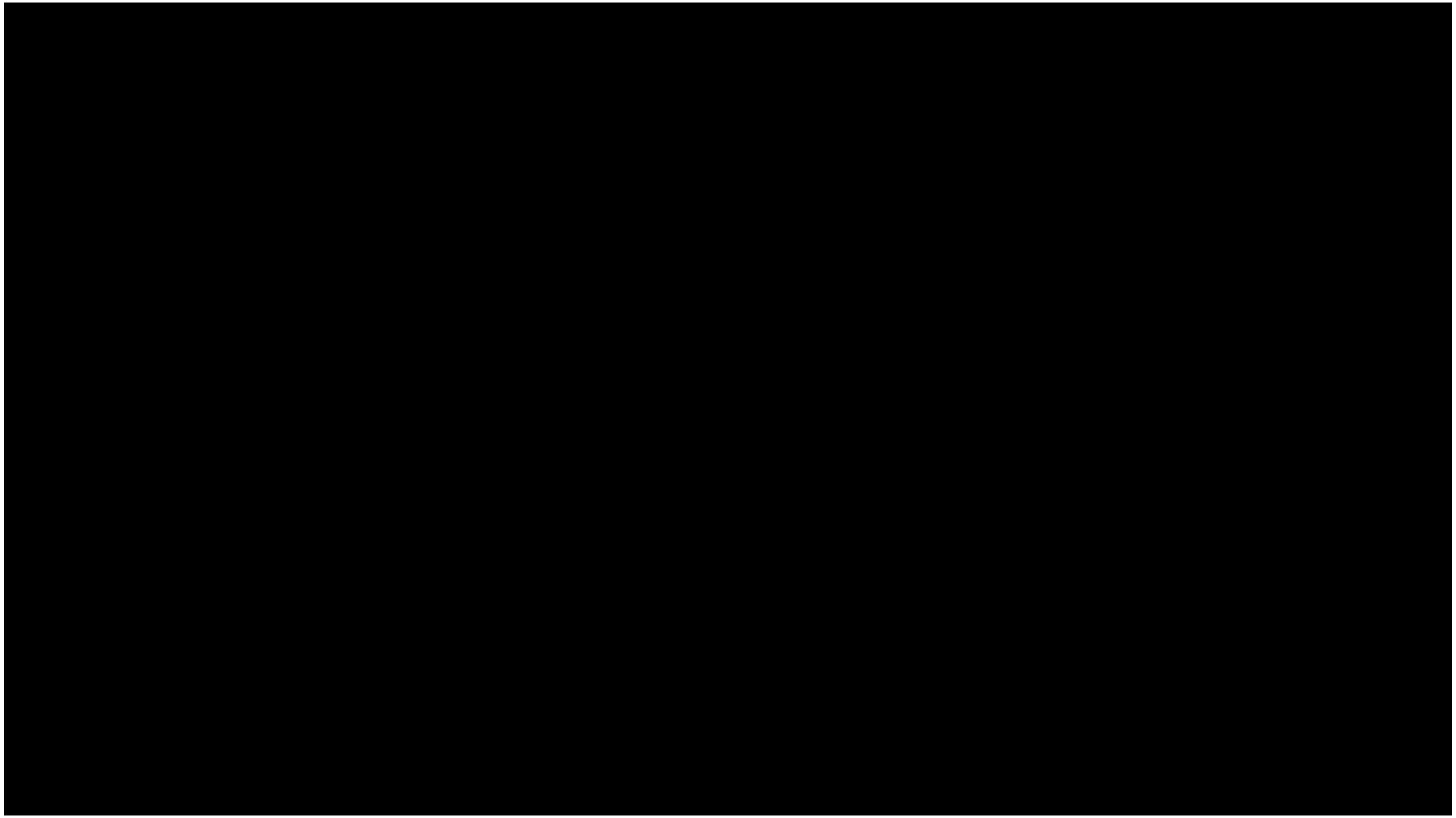
from
wikipedia.com

Time Standard

- NIST maintains time standard for U.S.
  - NIST-F2: http://www.nist.gov/pml/div688/nist-f2-atomic-clock-040314.cfm
- International Atomic Time (TAI)
  - Weighted average of 400 atomic clocks in 50 national labs
  - http://www.timeanddate.com/time/international-atomic-time.html
- Distribution of reference time
  - Network Time Protocol (NTP)
  - Radio (WWV station in Fort Collins, CO)
  - GPS
  - …

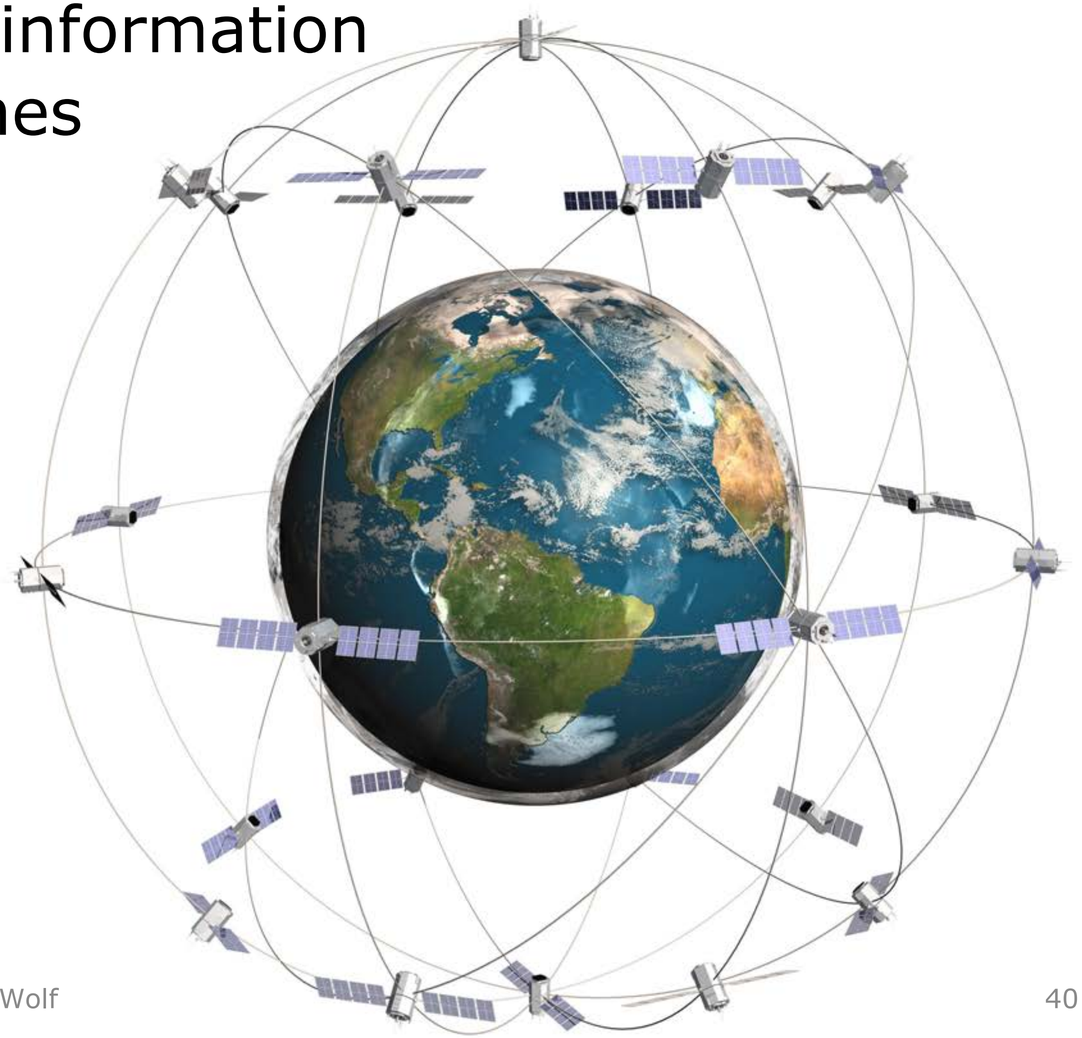
Atomic Clock

- https://www.youtube.com/watch?v=z-jE7DXy1x0



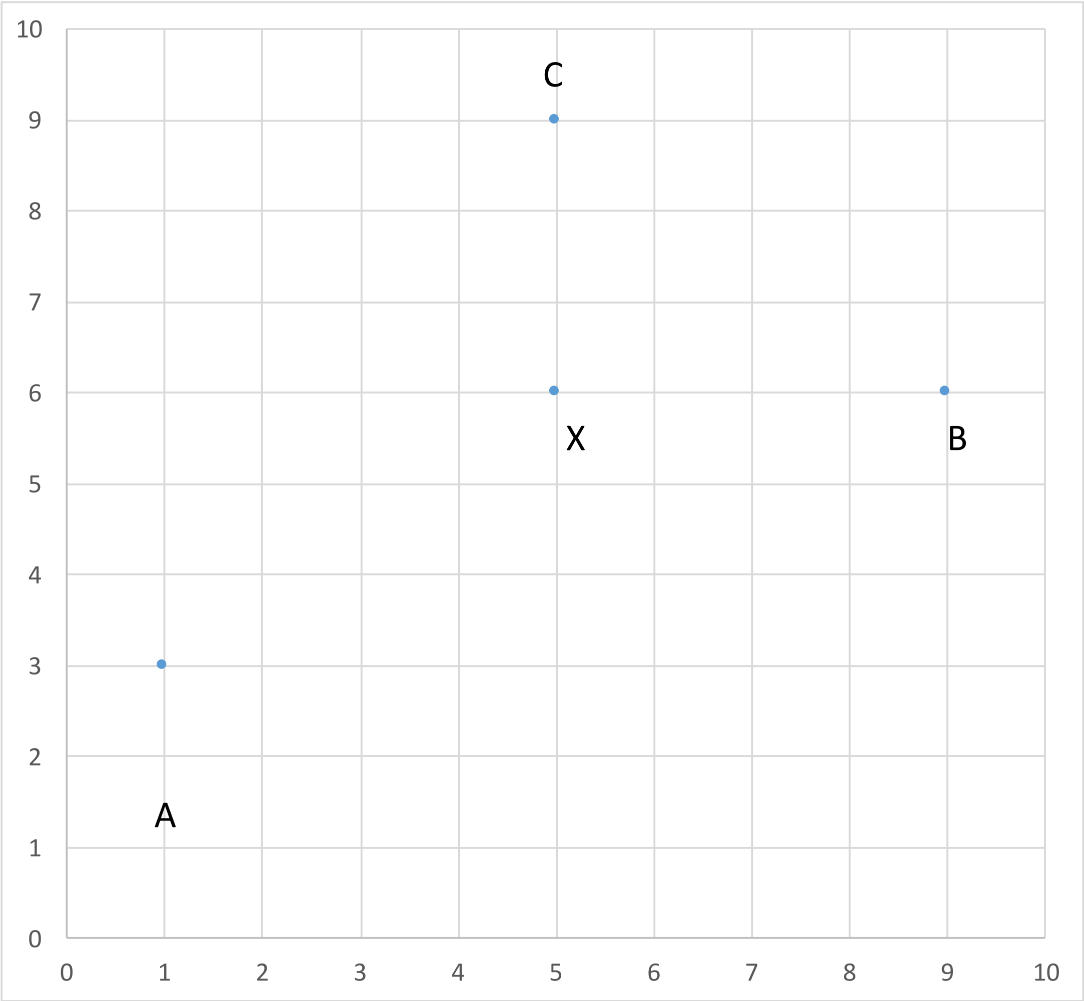
Global Positioning System

- 29 Satellites on known orbits send periodic signals
  - Signal contains very accurate time information
  - At least 4 satellites visible at all times at any location
- How can we determine location with this information?
  - Signal propagation delay is at core of solution



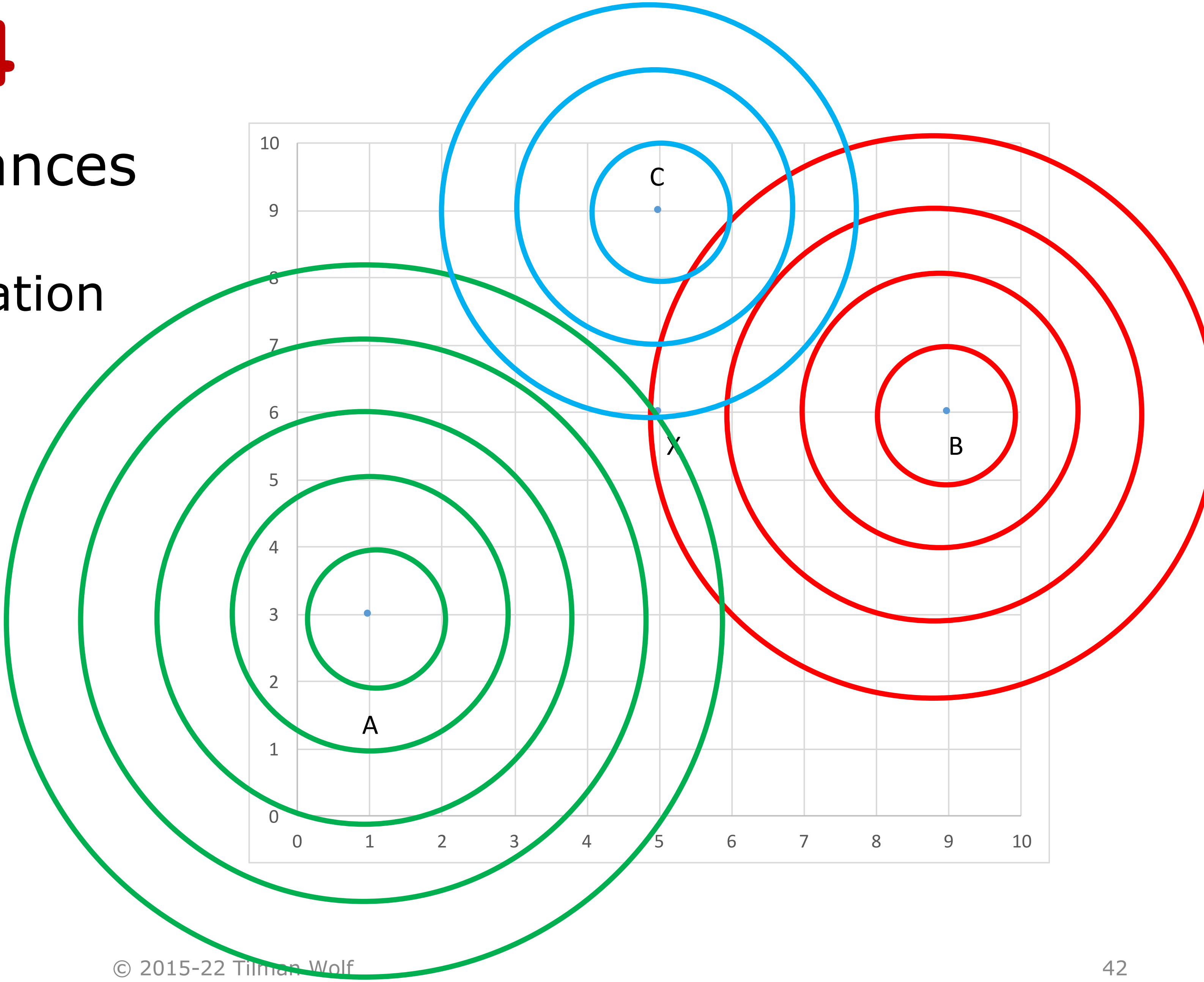
Trilateration 1/4

- Positioning using distances to reference points
  - Assume signal propagation speed of 1 unit/ms
- What are the delays observed at X?



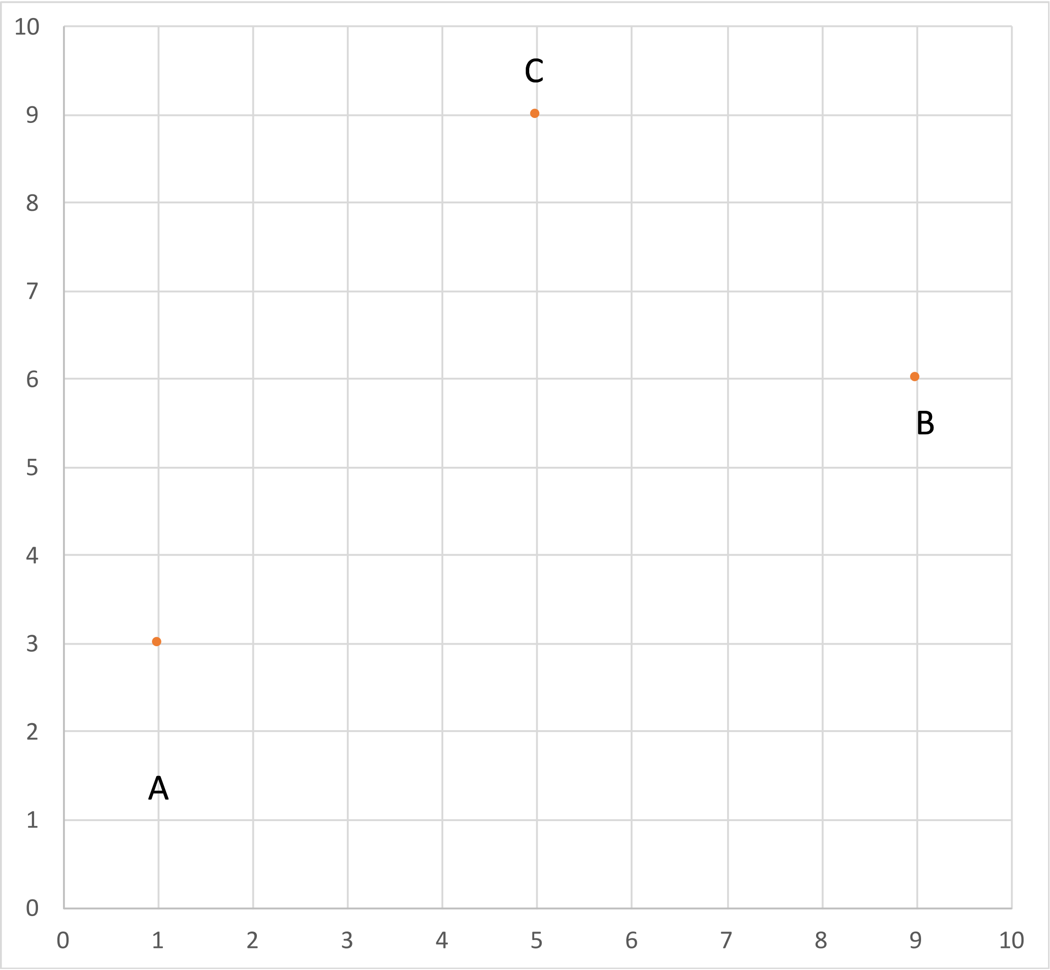
Trilateration 2/4

- Positioning using distances to reference points
  - Assume signal propagation speed of 1 unit/ms
- What are the delays observed at X?
  - A is 5 ms behind
  - B is 4 ms behind
  - C is 3 ms behind



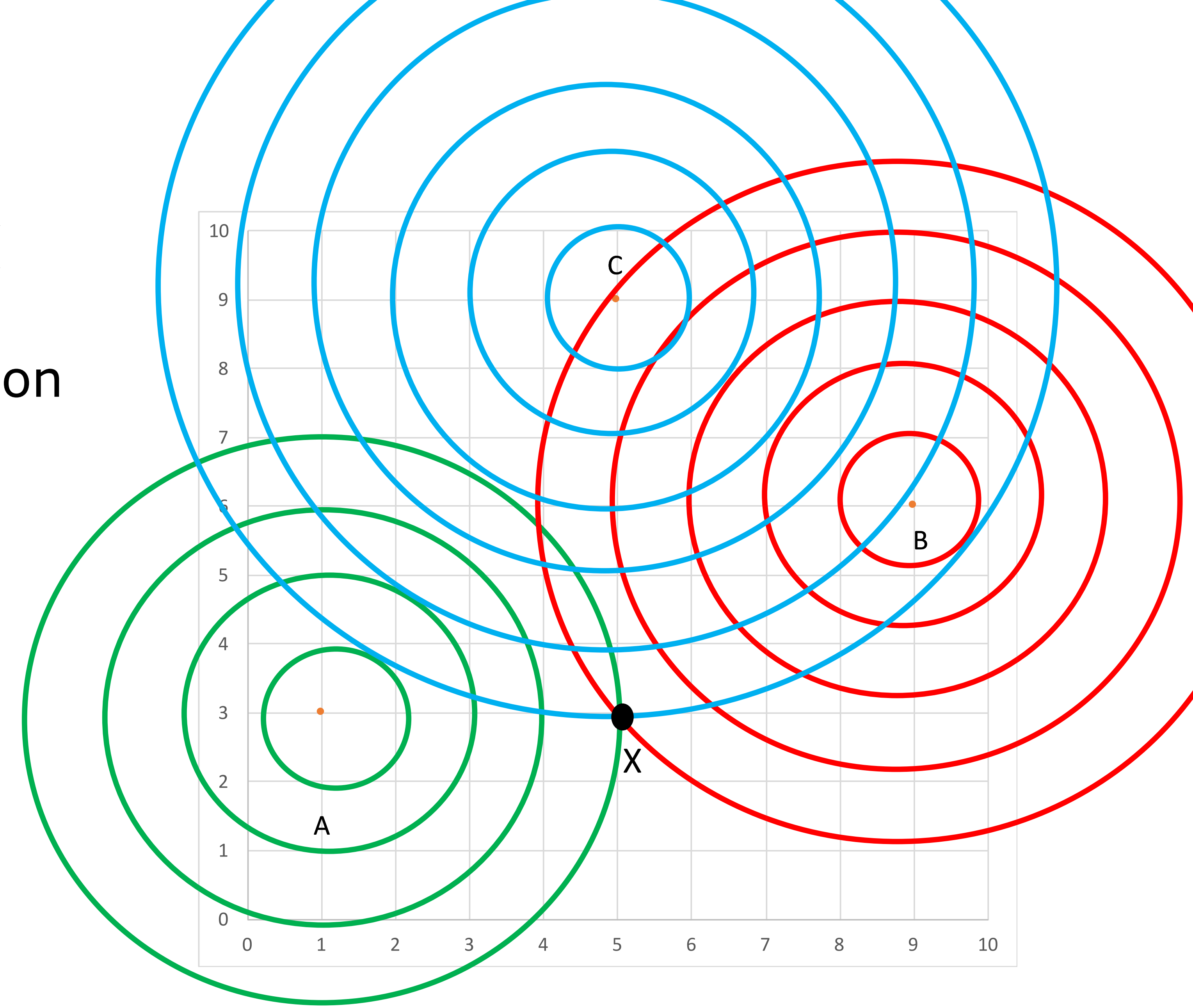
Trilateration 3/4

- Determine position of X based on delays
  - Assume signal propagation speed of 1 unit/ms
  - A-X: 4 ms
  - B-X: 5 ms
  - C-X: 6 ms



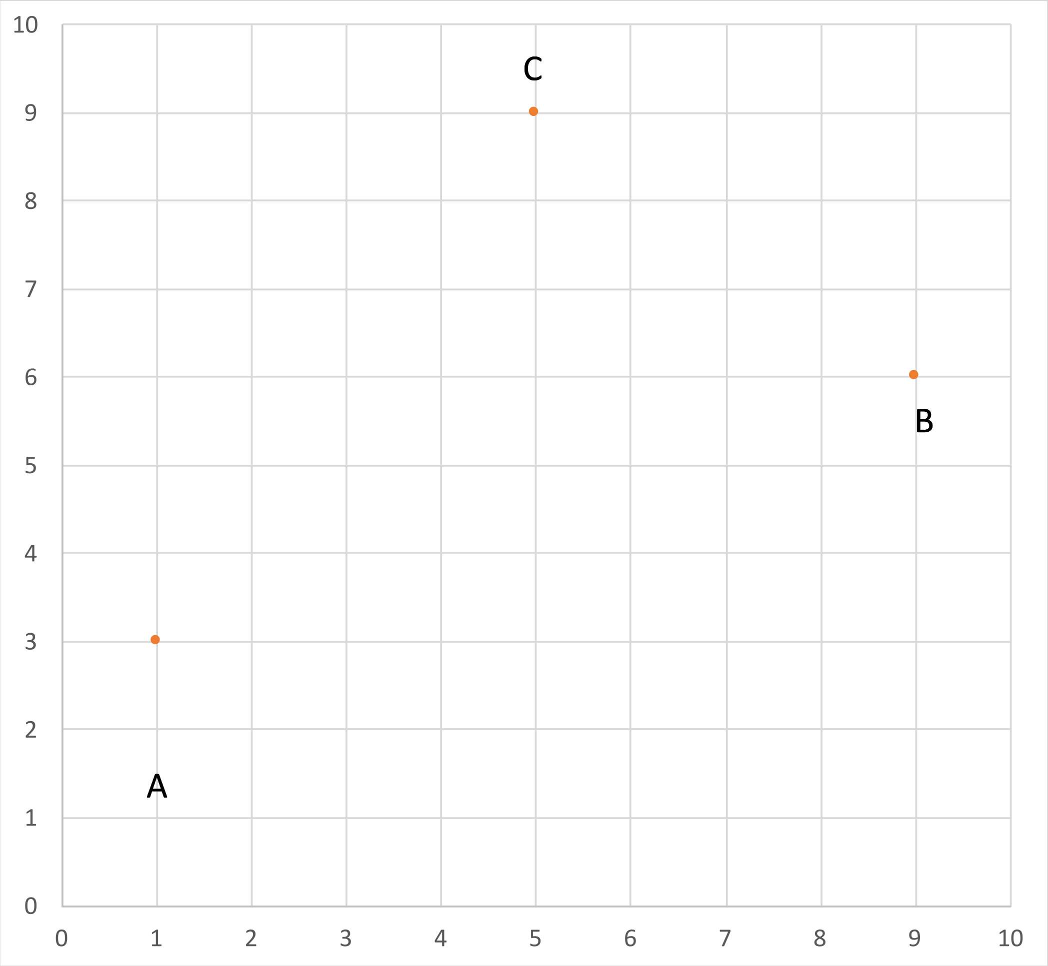
Trilateration 4/4

- Determine position of X based on delays
  - Assume signal propagation speed of 1 unit/ms
  - A-X: 4 ms
  - B-X: 5 ms
  - C-X: 6 ms



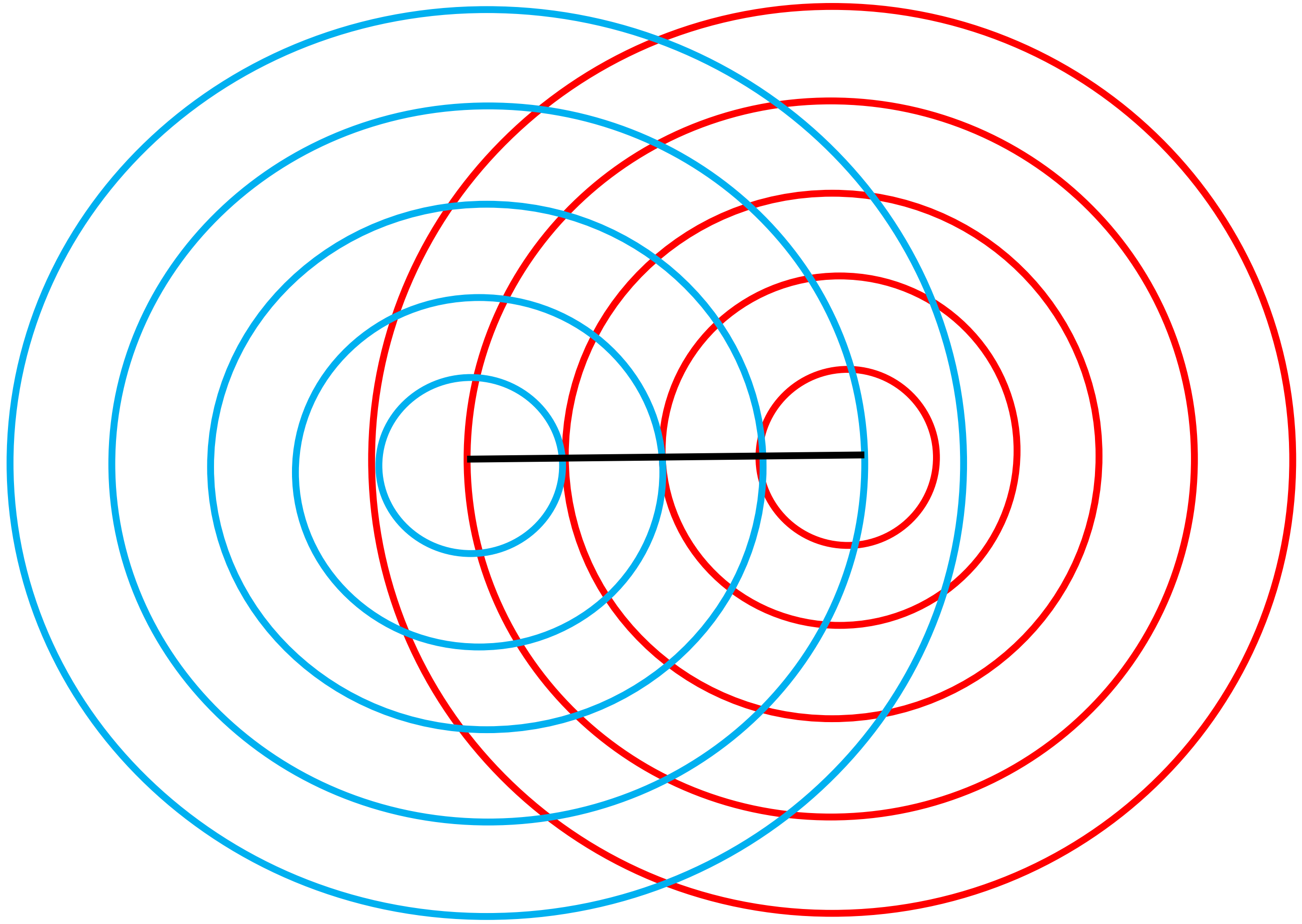
Multilateration 1/4

- Determine position of X based on delay differences
  - Assume signal propagation speed of 1 unit/ms
  - A-B: A 5 ms ahead
  - A-C: A 2 ms ahead
  - B-C: C 3 ms ahead



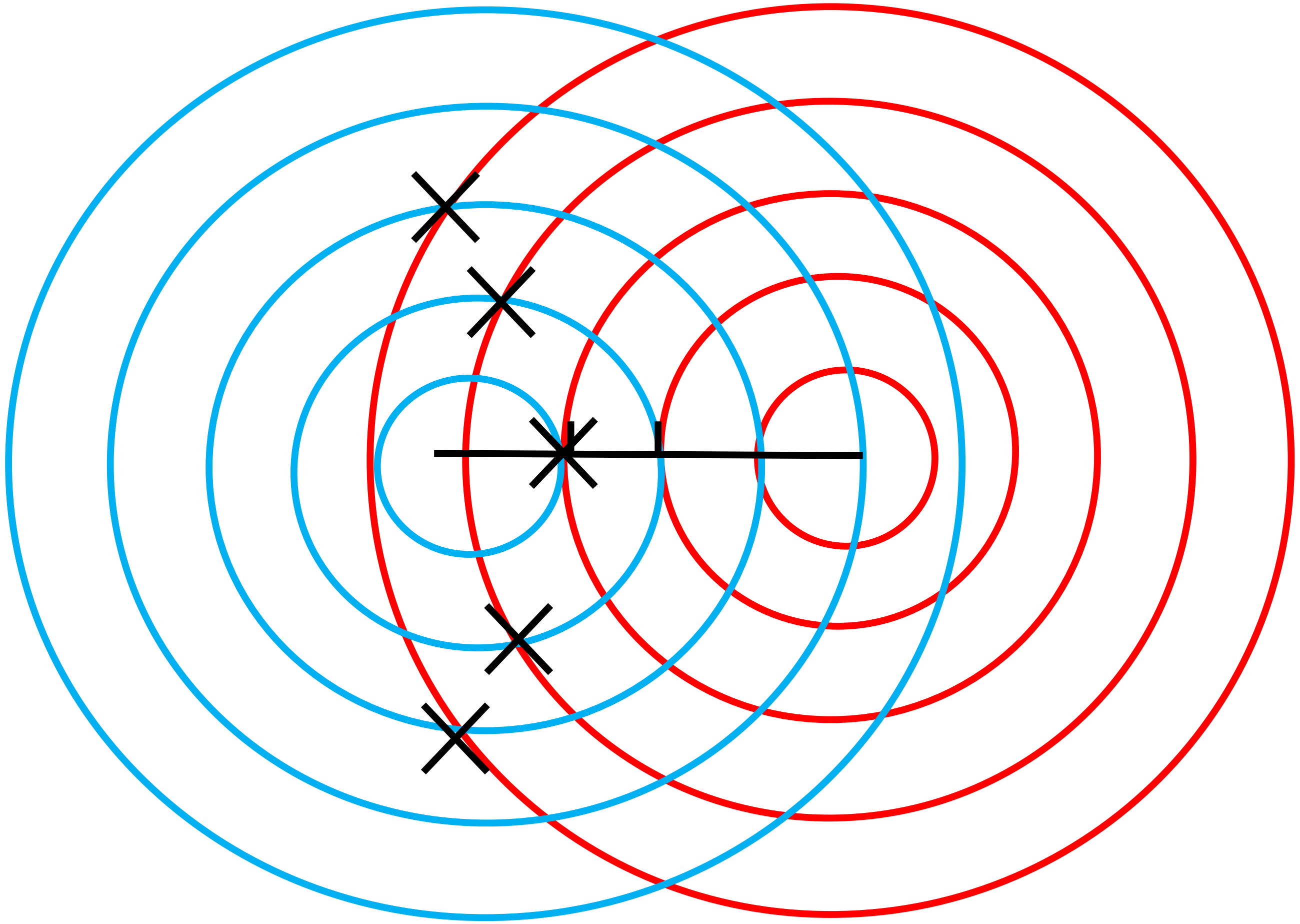
Multilateration 2/4

- Determining location based on delay difference
  - Example, blue ahead by 2 units



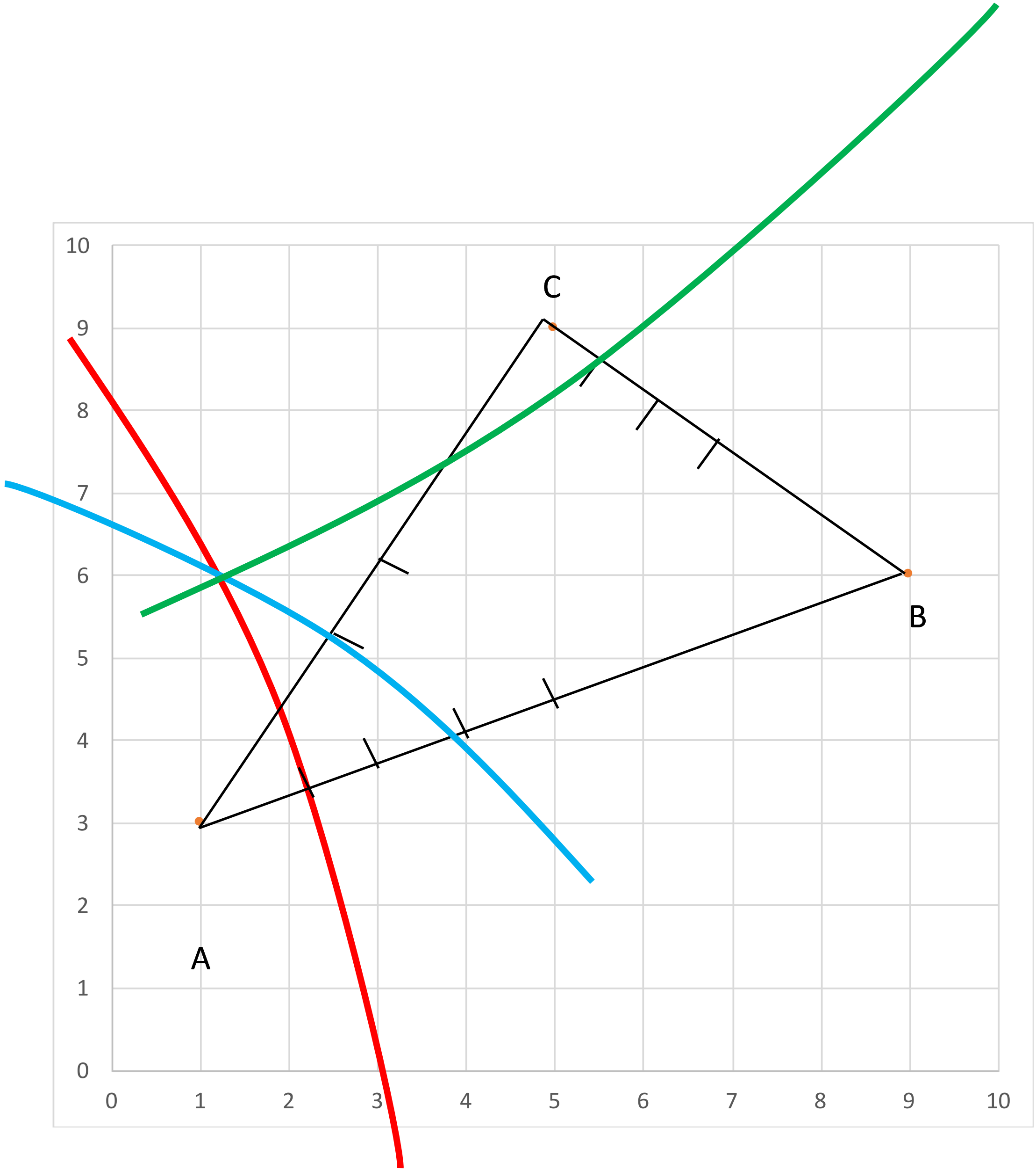
Multilateration 3/4

- Determining location based on delay difference
  - Example, blue ahead by 2 units



Multilateration 4/4

- Determine position of X based on delay differences
  - Assume signal propagation speed of 1 unit/ms
  - A-B: A 5 ms ahead
  - A-C: A 2 ms ahead
  - B-C: C 3 ms ahead



Global Positioning System Operation

- Multilateration to determine position of receiver
  - Requires at least 3 satellites (when on earth surface)
  - Requires at least 4 satellites for altitude
- Satellites transmit on same frequency
  - Different modulations
- GPS provides location and time
  - Global time adjusted to local time by knowing time zone

GPS Satellites

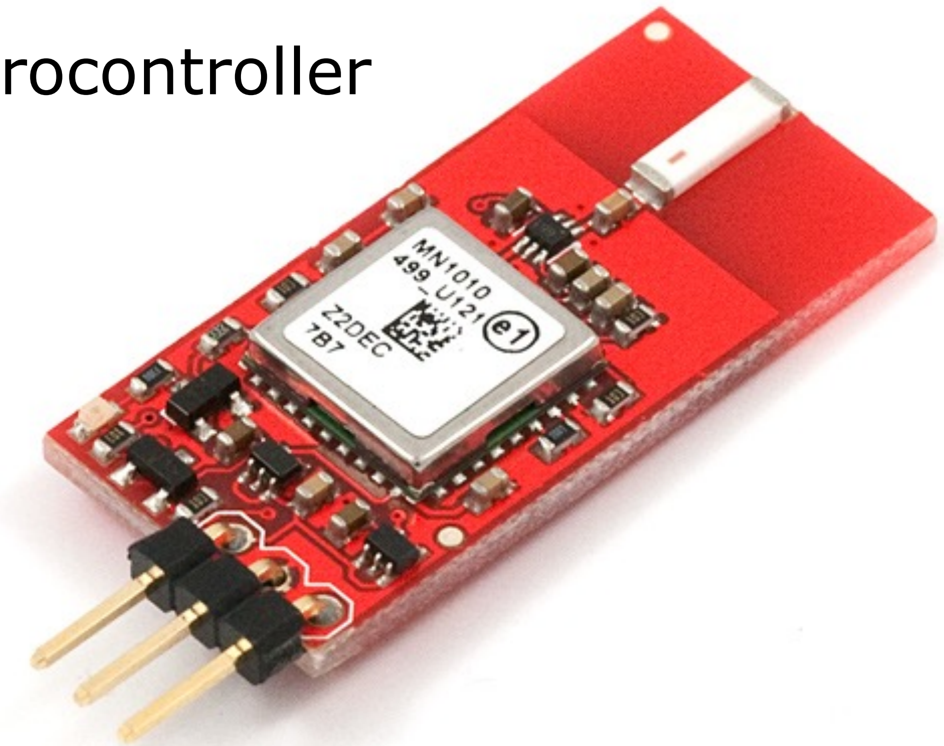
GPS Receiver

- Traditional receiver with antenna

- Embedded receiver

GPS Demo 1/2

- GPS receiver very small
- GPS interface very easy to use
  - Simple serial connection
  - 3 wires for data and power
  - Can connect directly to computer or microcontroller
- Example:

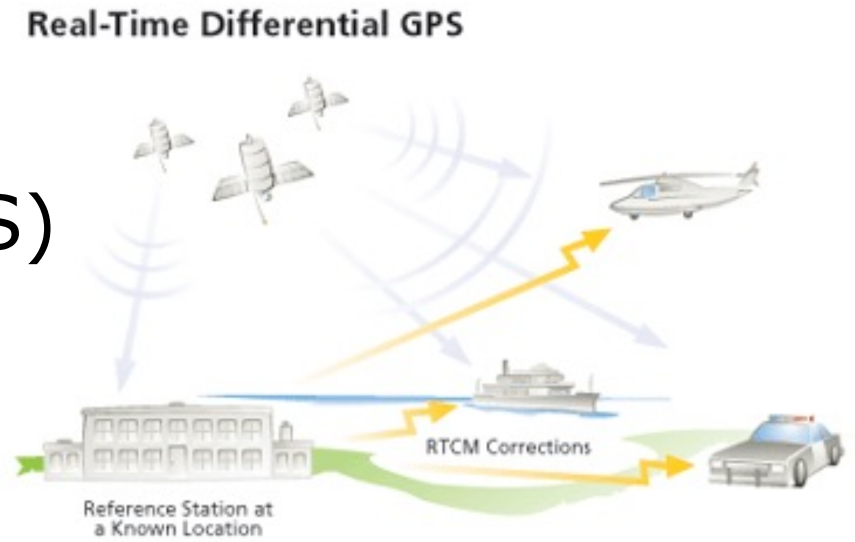


GPS Demo 2/2

- GPS sends information periodically
- GPS messages
  - Location, precision, time, speed, etc.
- Example:
  - `$GPRMC,225446,A,4916.45,N,12311.12,W,000.5,054.7, 191194,020.3,E*68`
  - Interpretation:
    - `225446` Time of fix 22:54:46 UTC
    - `A` Navigation receiver warning A = Valid position, V = Warning
    - `4916.45,N` Latitude 49 deg. 16.45 min. North
    - `12311.12,W` Longitude 123 deg. 11.12 min. West
    - `000.5` Speed over ground, Knots
    - `054.7` Course Made Good, degrees true
    - `191194` UTC Date of fix, 19 November 1994
    - `020.3,E` Magnetic variation, 20.3 deg. East
    - `*68` Mandatory checksum

GPS Limitations

- Requires view of sky
  - Does not work indoors
  - Difficult with foliage, high-rise buildings
- Accuracy limited
  - Horizontal accuracy in the order of tens of feet
- Differential GPS
  - Reference to known location
  - Correction broadcast via UHF
- Wide Area Augmentation System (WAAS)
  - Reference to know location
  - Correction broadcast via satellites
  - WAAS-enabled receivers can compensate

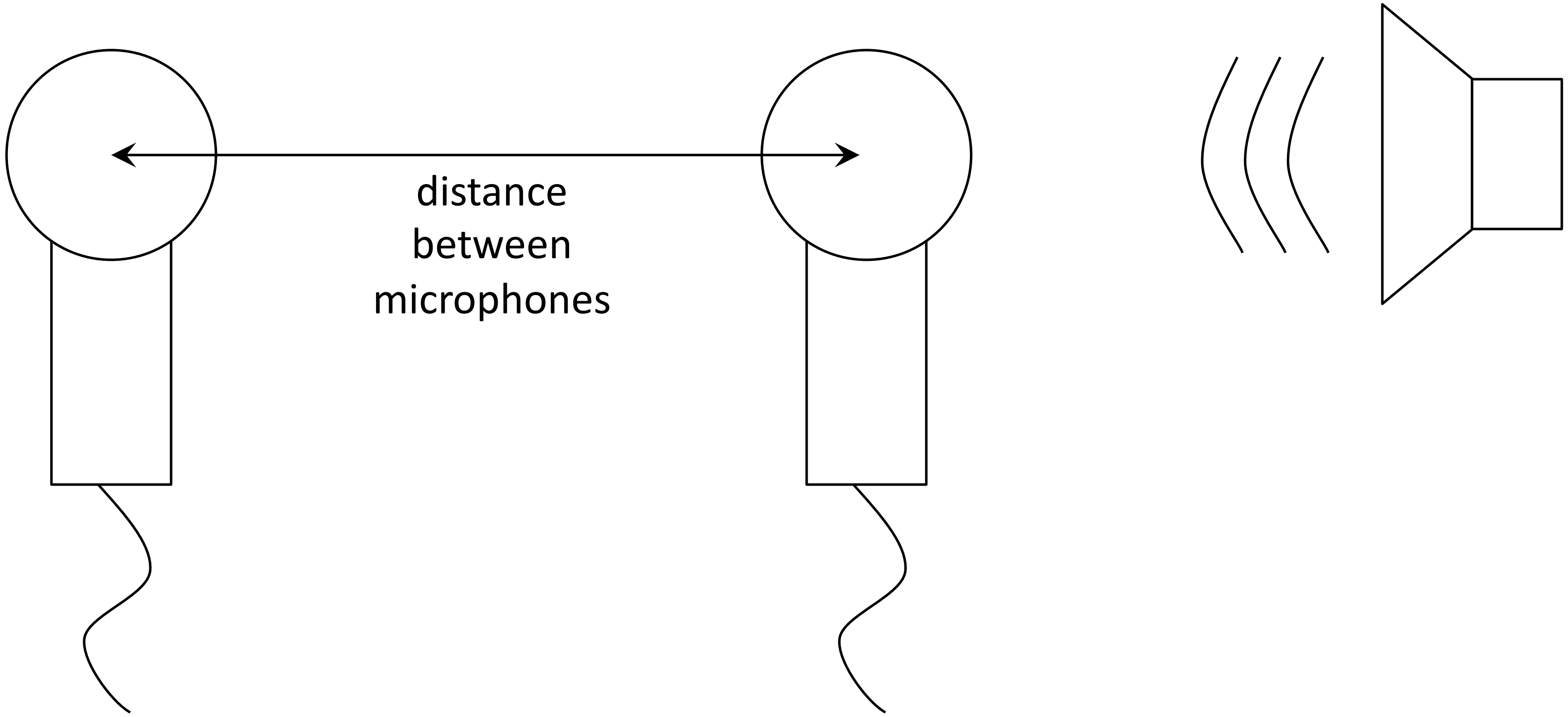


Propagation Delay of Signals 1/5

- Signals propagate with finite speed
  - Longer travel distance incurs longer delay
- Use delay to infer information about environment
  - Direction, distance, etc.
- Propagation speed is important
  - Propagation speed of sound: 340 m/s
  - Propagation speed of light: 300,000,000 m/s
- Choice of signal type matters greatly in system implementation

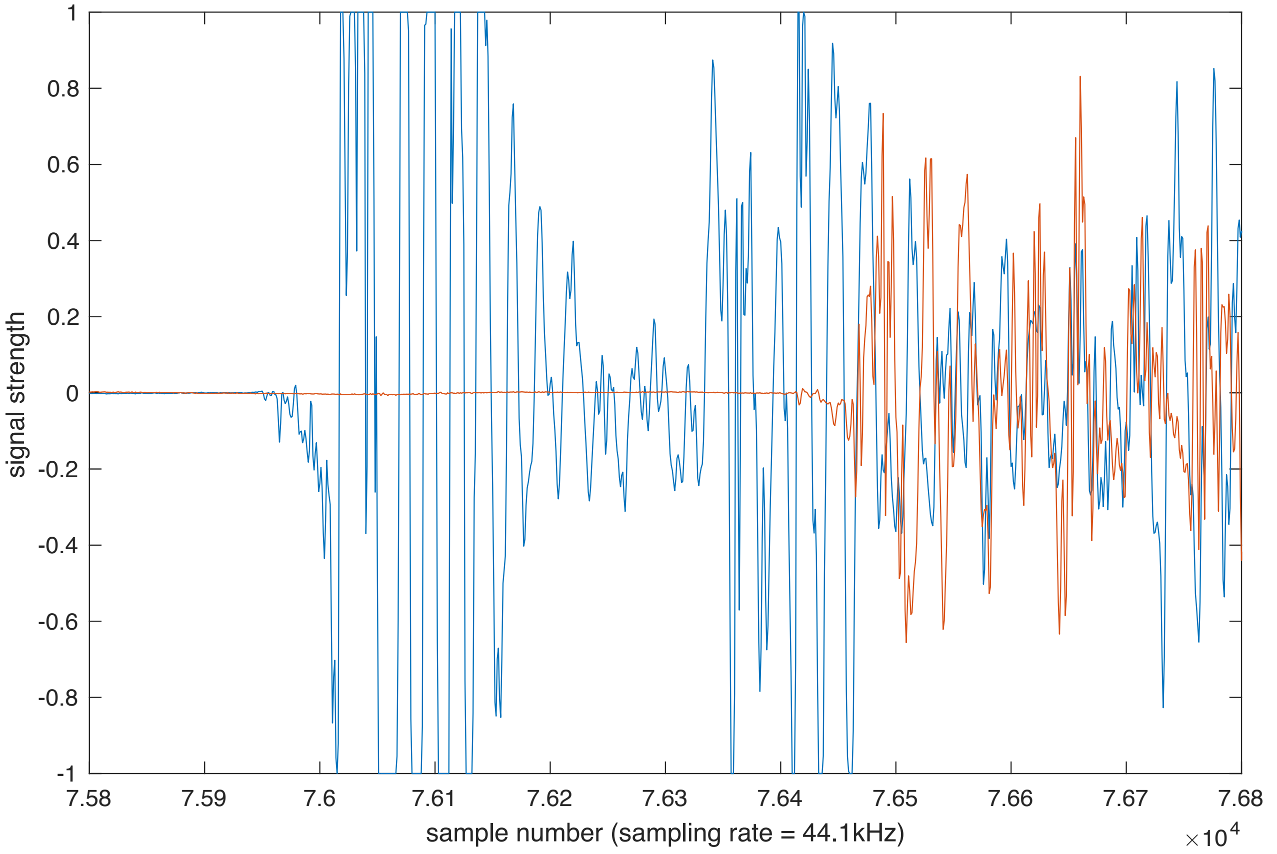
Propagation Delay of Signals 2/5

- Example: audio recording by two microphones
  - What do we expect to see in the signals?



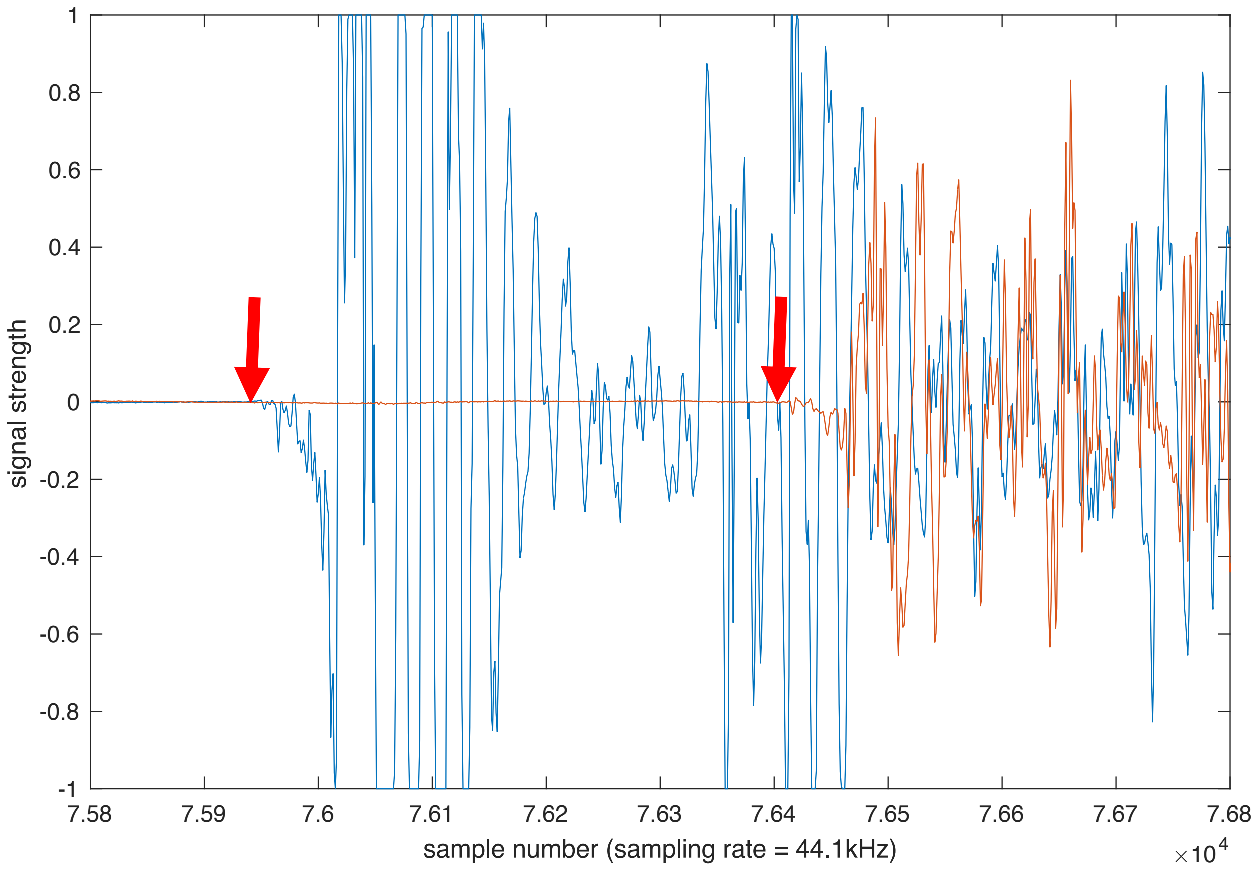
Propagation Delay of Signals 3/5

- Example: audio recording by two microphones
  - What is the distance between microphones (in direction of signal propagation)?



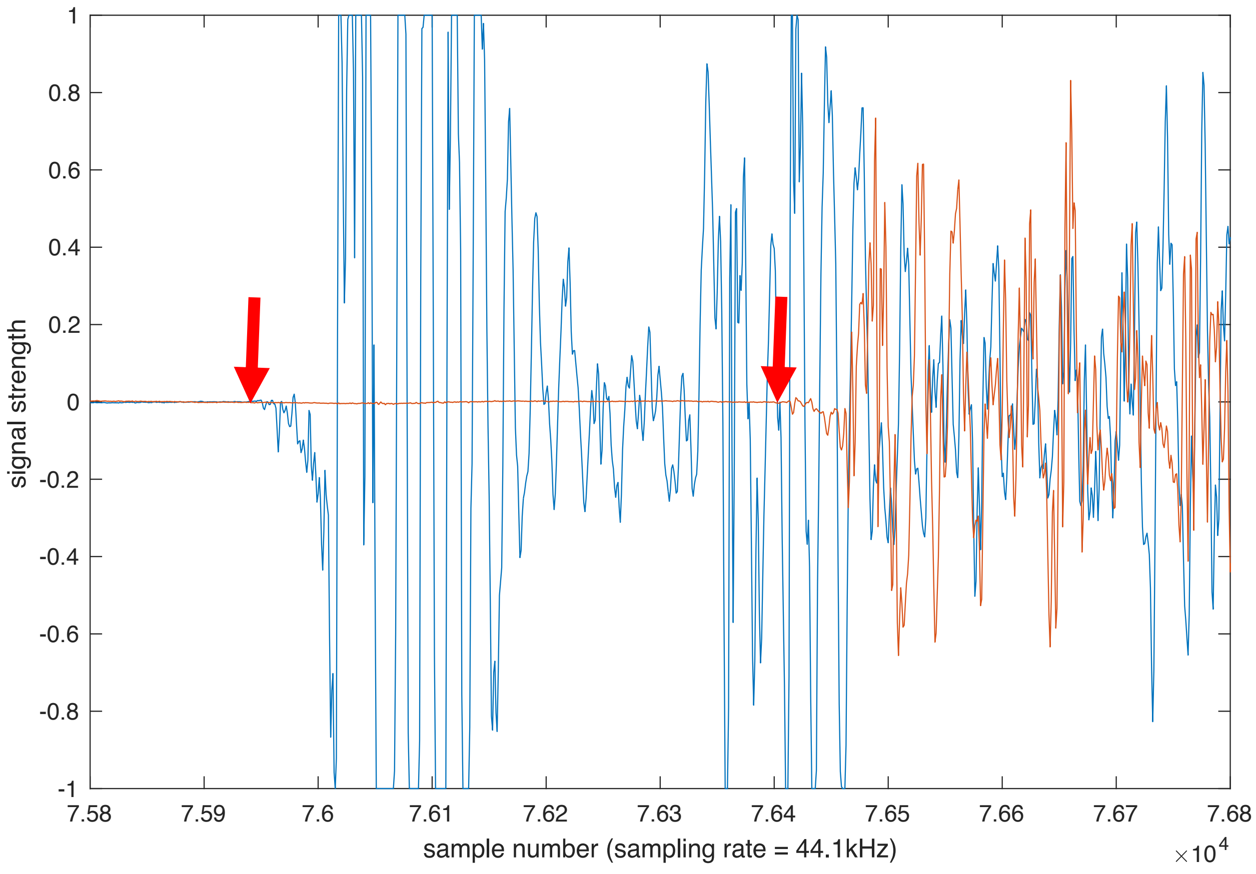
Propagation Delay of Signals 4/5

- Can we calculate the distance from the recording?
- Information about signal:
  - Propagation speed 340 m/s
  - Sampling rate 44.1kHz



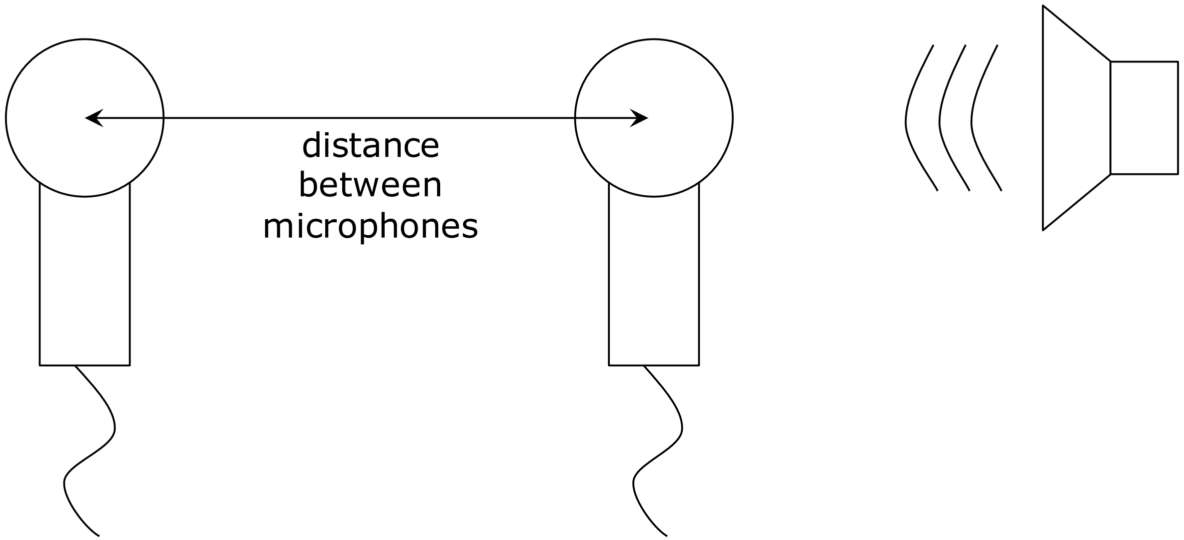
Propagation Delay of Signals 5/5

- Can we calculate the distance from the recording
- Information about signal:
  - Propagation speed 340 m/s
  - Sampling rate 44.1kHz
- Distance between signals: ~460 samples
  - Delay = samples / sampling rate = 460/44100 s = 0.0104 s
- Distance between microphones
  - Distance =
    = delay * prop. speed =
    = 0.0102 s * 340 m/s =
    = 3.55 m



Distance Measurement

- Audio recording from two microphones
  - Estimate distance with MATLAB



Editor – /Users/wolf/Documents/Teaching/Courses/ENGIN112/...

distance.m

```
%reading audio files
file1 = 'TASCAM_0089S12.wav';
[y,Fs]=audioread(file1);
%ch(0) = y(:,1);
%ch(1) = y(:,2);


range=1:100000;
x=(range);

plot(x,y(range,1))
ax = gca;
ax.XAxis.Exponent = 0;
xtickformat('%d')
hold on
plot(x,-y(range,2))
hold off
```

Distance Measurement Resolution

- What is the “resolution” of this measurement?
  - What is the “step size” in which we can measure distance?
- Distance for one sample
  - 340 m/s / 44,100 samples/s = 7.7 mm
- Distance can be measured down to centimeter
  - Higher sampling rate gives finer resolution

Ultrasonic Sensor and Arduino 1/4

- Sensors use transmitter and receiver combo
  - Sends ultrasonic signal and listens to reflection
  - Delay determines distance

The HC-SR04 Ultrasonic Sensor is an affordable proximity/distance sensor t
robotics to car parking. The module has integral ultrasonic transmitters, rece
boards.

Working Voltage: **DC 5V**

Output : **5V**

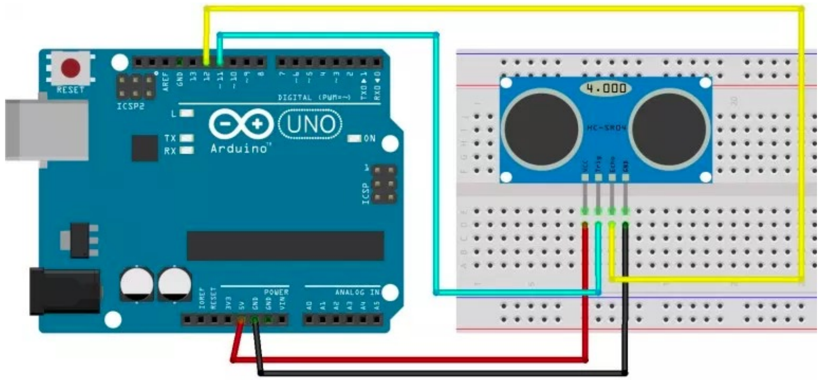
Static Current: **2mA**

Detection Distance : **20 ~ 4500mm**

Resolution: **>2mm**

Dimensions : **45 x 27 x 17mm**

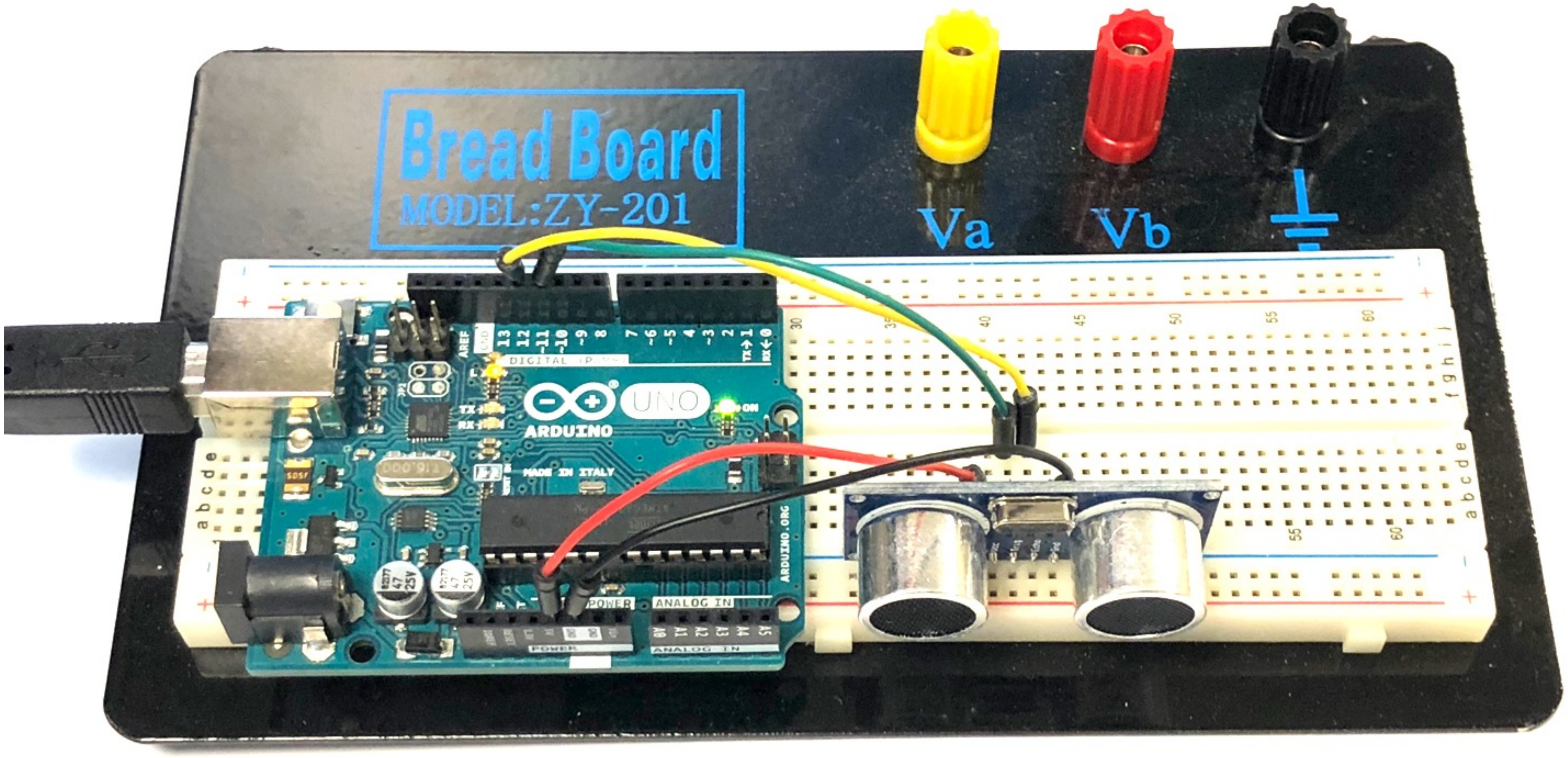
Weight : **9g**



From:
randomnerdtutorials.com

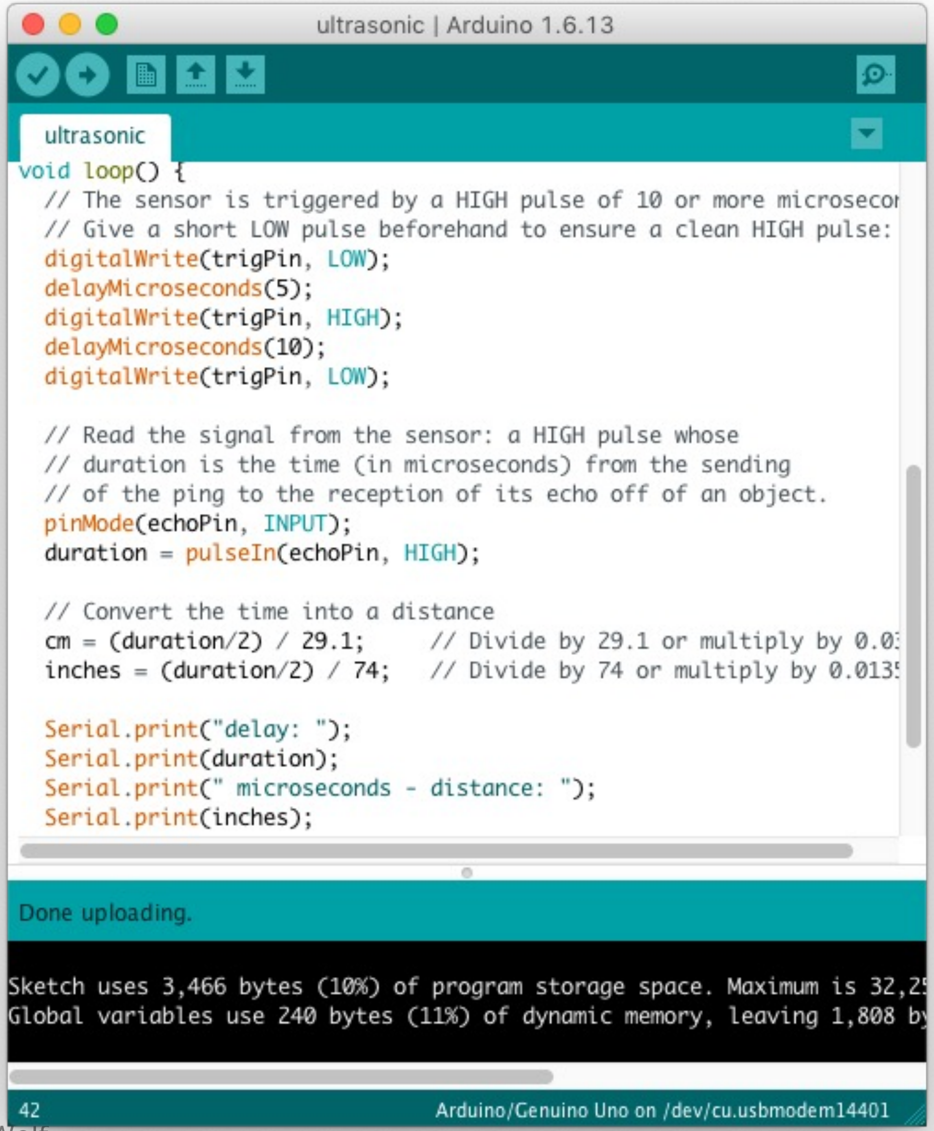
Ultrasonic Sensor and Arduino 2/4

- Implementation:



Ultrasonic Sensor and Arduino 3/4

- Code:
  - Pulse sent to sensor
  - Measure time until sensor detects response
  - Convert delay into distance
  - Print result



Ultrasonic Sensor and Arduino 4/4

- Arduino output:
  - Check (first result):
    - 1289μs * 340m/s = 0.438m (round trip)
    - 0.438m / 2 = 0.219m = 22cm (one-way distance)

/dev/cu.usbmodem146240 (Arduino/Genuino Uno)

Send

```
delay: 1289 microseconds - distance: 8in, 22cm
delay: 1238 microseconds - distance: 8in, 21cm
delay: 1211 microseconds - distance: 8in, 20cm
delay: 1298 microseconds - distance: 8in, 22cm
delay: 1325 microseconds - distance: 8in, 22cm
delay: 1337 microseconds - distance: 9in, 22cm
delay: 1394 microseconds - distance: 9in, 23cm
delay: 1453 microseconds - distance: 9in, 24cm
delay: 1634 microseconds - distance: 11in, 28cm
delay: 2167 microseconds - distance: 14in, 37cm
delay: 12485 microseconds - distance: 84in, 214cm
delay: 12363 microseconds - distance: 83in, 212cm
delay: 12384 microseconds - distance: 83in, 212cm
delay: 12413 microseconds - distance: 83in, 213cm
delay: 12389 microseconds - distance: 83in, 212cm
delay: 12363 microseconds - distance: 83in, 212cm
```

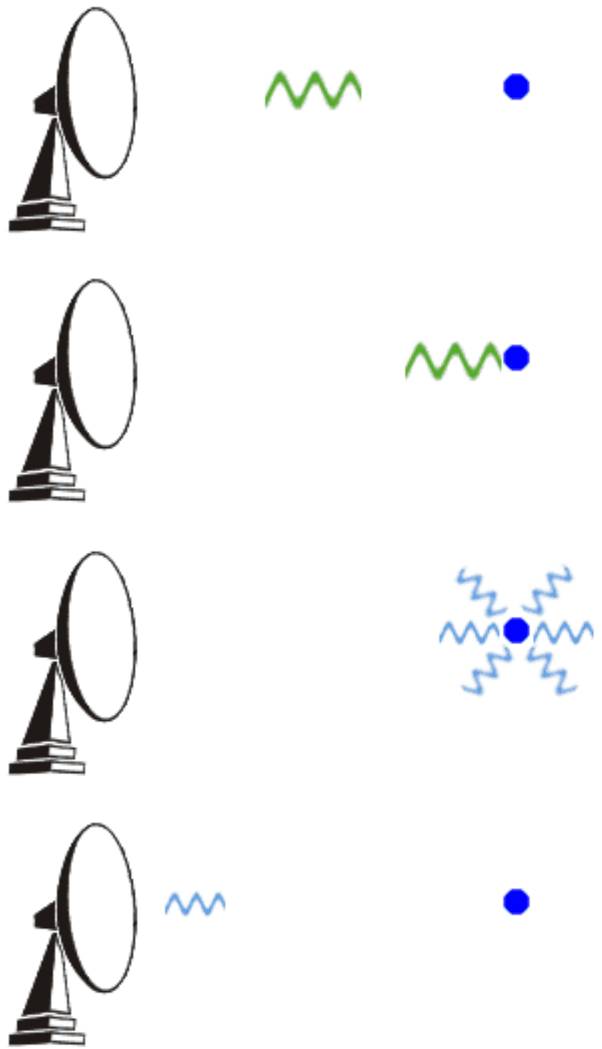
Autoscroll | No line ending | 9600 baud

Side Note: Micromouse

- Annual IEEE competition
  - UMass won 2014 and 2015 regional competitions
  - Video: https://www.youtube.com/watch?v=CNbWBfzuFnU
  - Positioning relative to absolute reference (wall) using ultrasonic sensor

Principles of Radar

- RAdio Detection And Ranging (RADAR)
  - Radar transmits short pulse of radio signal
    - Typically 1–60GHz
  - Signal reflects/scatters off object
  - Reflected signal travels back to radar
  - Round-trip time proportional to distance of object
    - Pulse propagates at speed of light
- Radar needs to switch from sending to receiving
  - No simultaneous send and receive
- Tradeoff
  - Longer pulses easier to detect
  - Shorter pulses lower minimum range

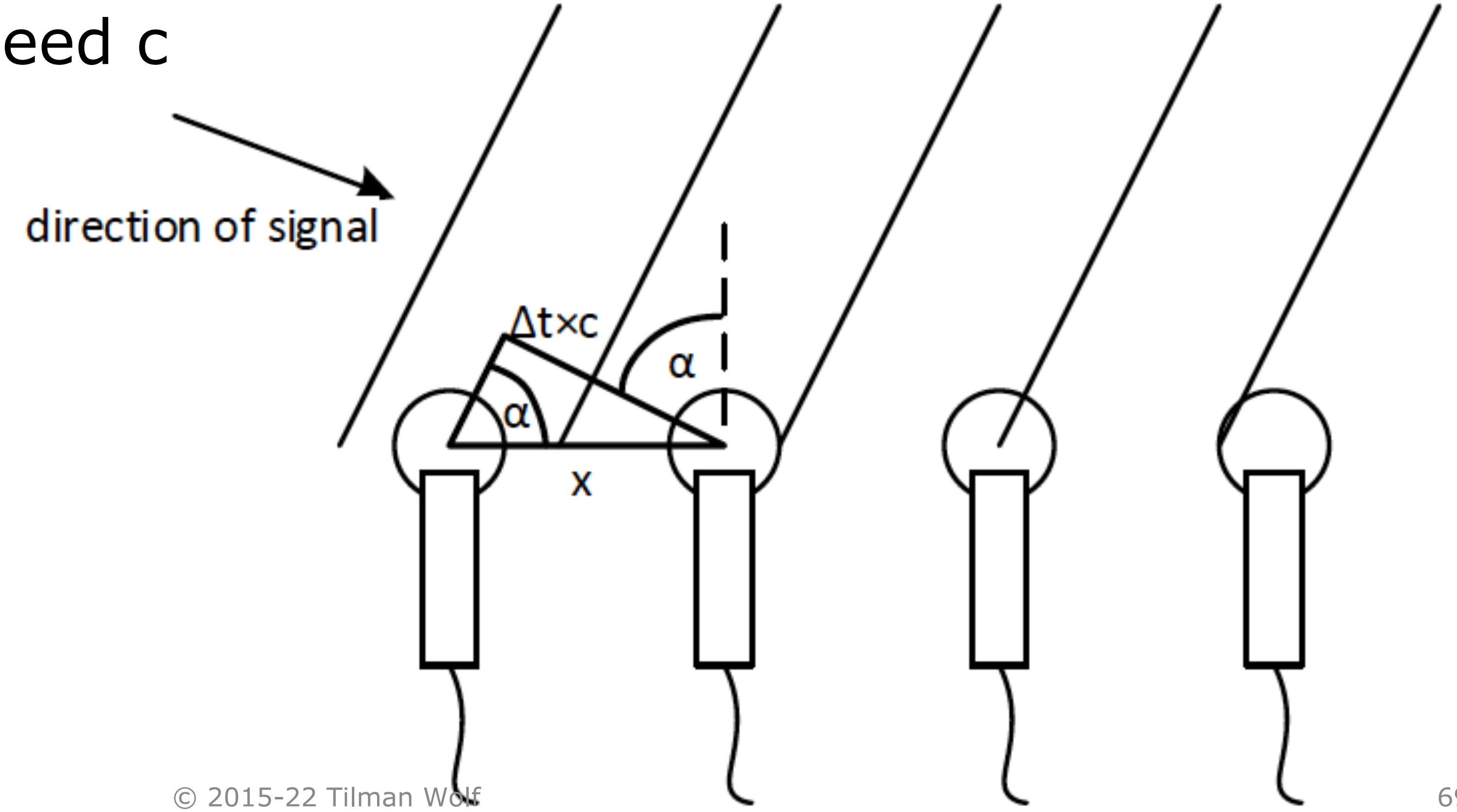


Air Traffic Control Radar

- Primary Surveillance Radar (PSR)
  - Determines distance of planes from reflection echo
  - Determines bearing from its rotation at time of transmission
  - Cannot determine altitude of plane
- Secondary Surveillance Radar (SSR)
  - Triggers airplane transponder
  - Receives messages from airplane transponder with altitude information
- SSR similar to IFF
  - “Identification friend or foe”
  - Used by military to authenticate airplanes

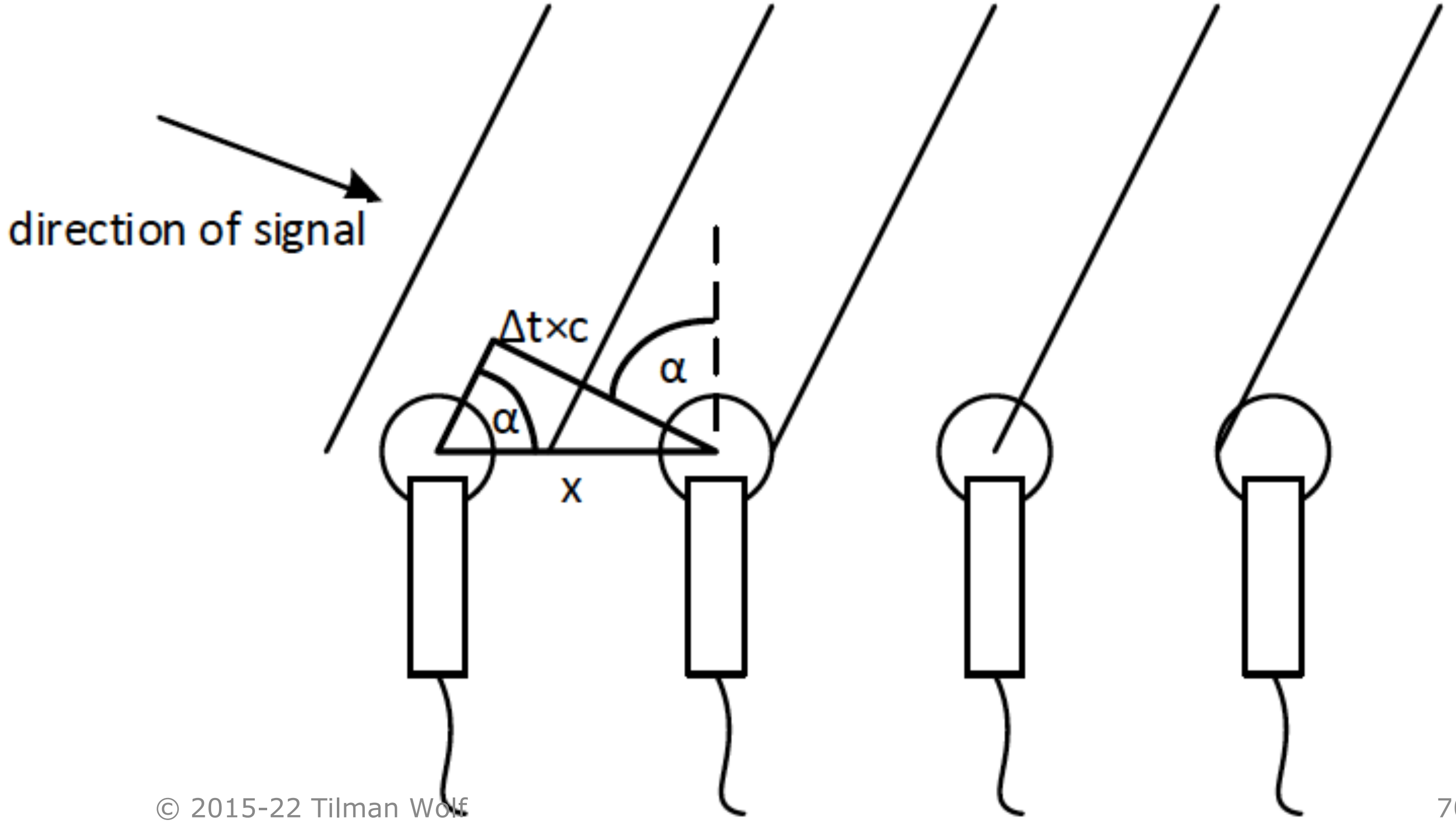
Beamforming 1/2

- Another example using signal delay
- Determine angle of signal arrival based on delay
  - Distance between microphones x
  - Signal propagation speed c
  - Arrival delay Δt
  - Angle of arrival α



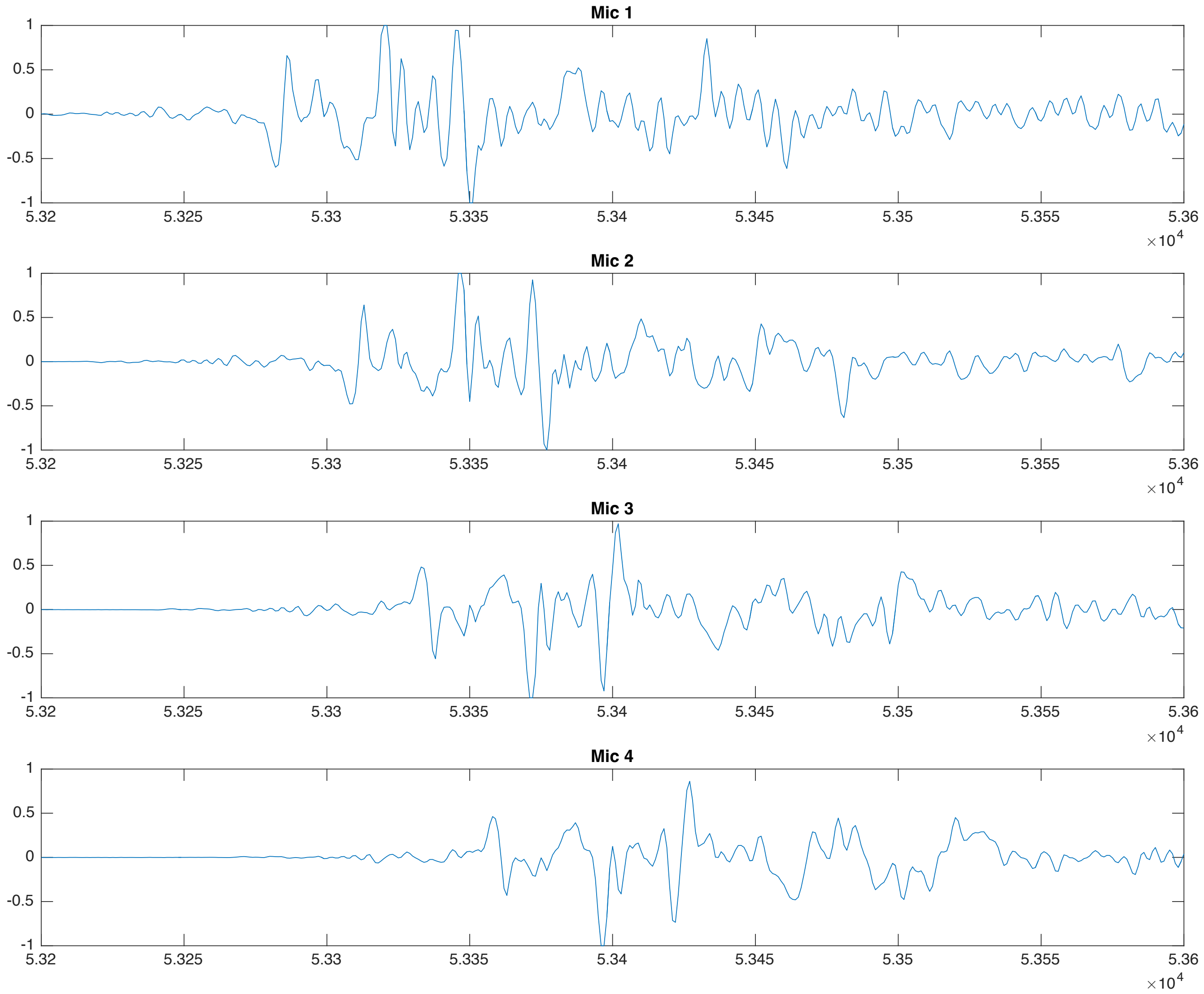
Beamforming 2/2

- How to determine angle of arrival?
  - Utilize rectangular triangle property: $\sin\alpha = \frac{\Delta t \times c}{x}$



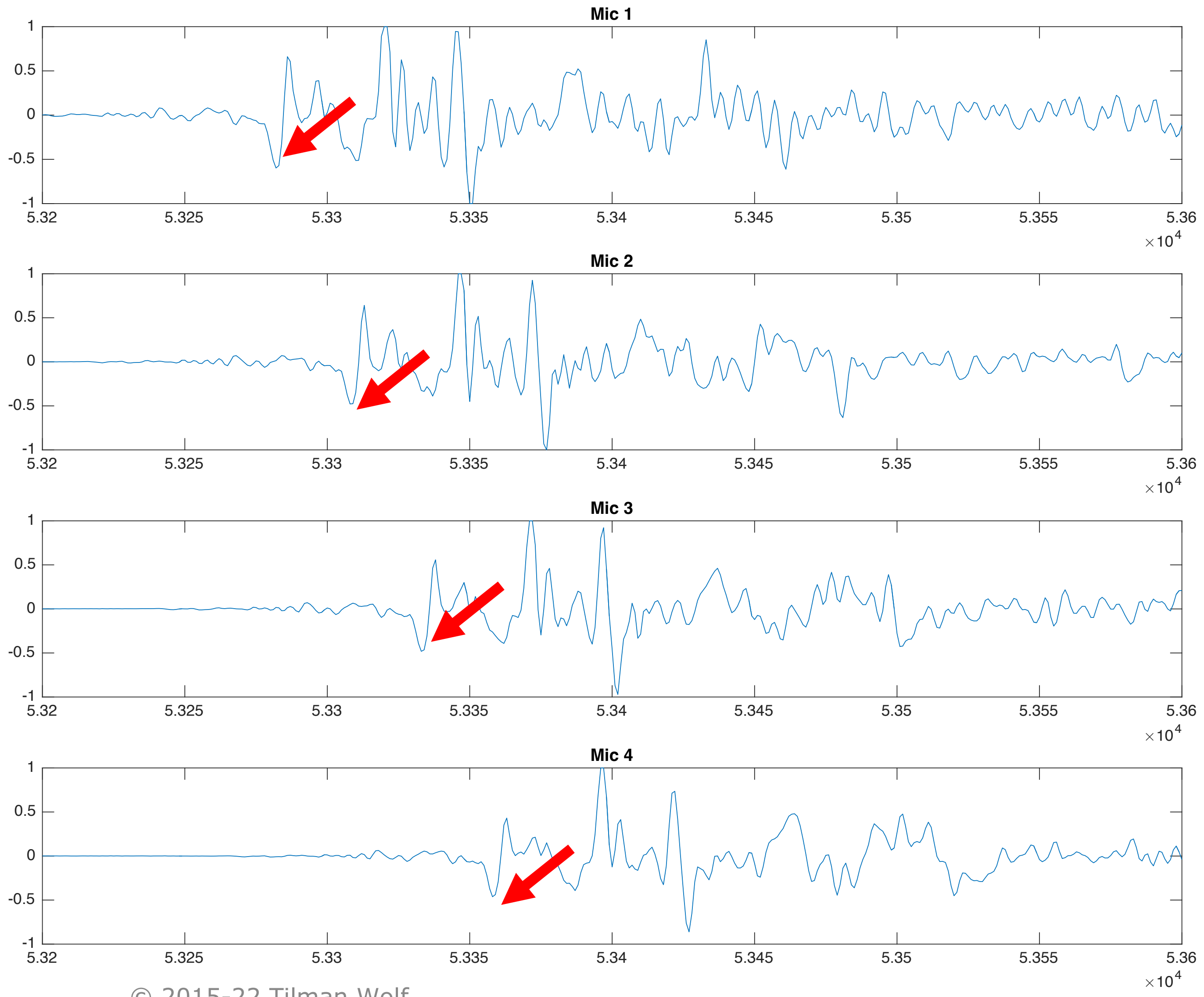
Beamforming Example 1/3

- Four microphones



Beamforming Example 2/3

- Peak delayed by ~ 30 samples



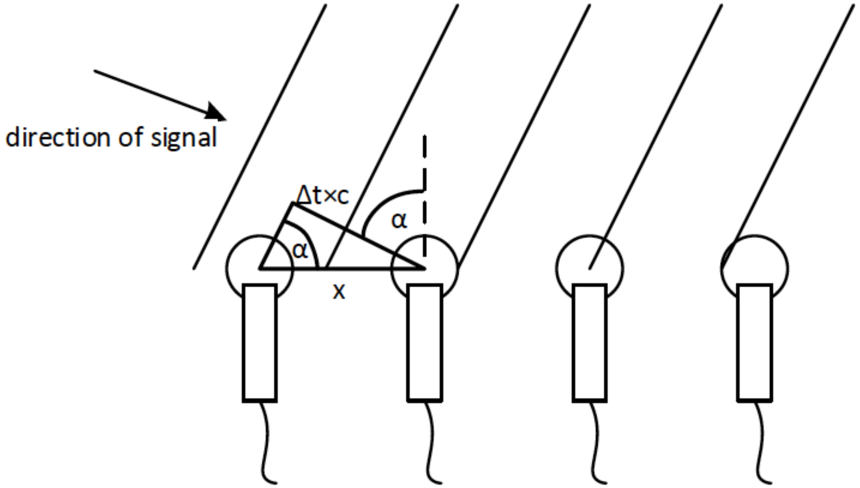
Beamforming Example 3/3

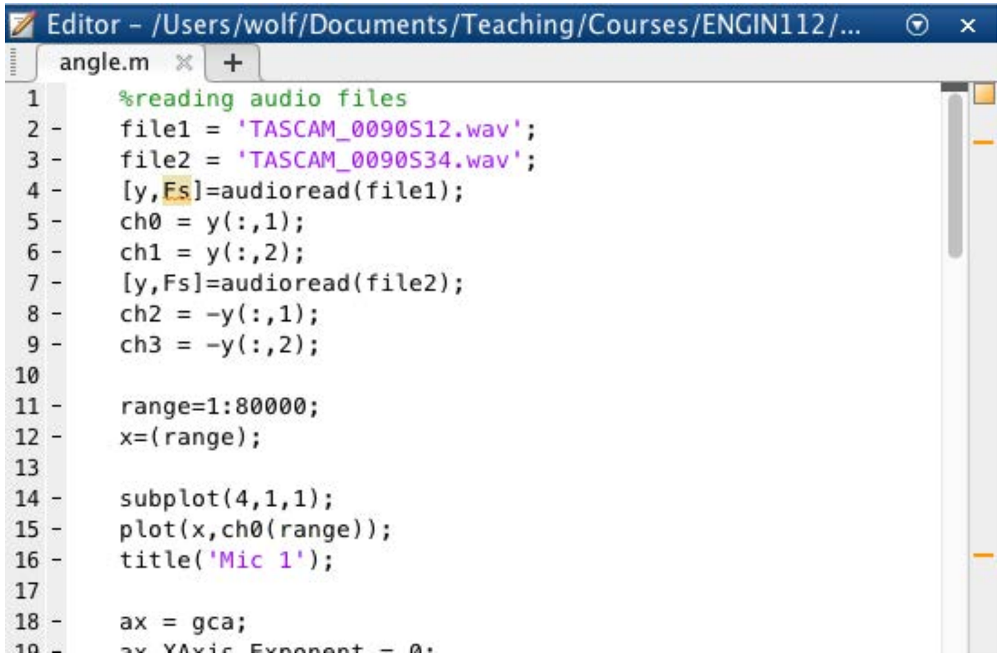
- Calculating angle
  - Delay: 20 samples / 44100 Hz = 0.45 ms
  - Distance: 0.45 ms * 340 m/s = 0.15 m
  - Distance between microphones: 0.2 m
  - Angle: $\sin\alpha = \frac{0.15m}{0.2m} = 0.771$
  - Angle in degrees: 48.7 (towards microphone 1)
- Aggregating samples to “listen” into one direction
  - Shift all signals by delay matching angle of direction
  - Sum samples

Beamforming Demonstration

- Audio recording on microphone array
  - Distance between microphones: 10 inches / 25.4 cm

$$\sin\alpha = \frac{\Delta t \times c}{x}$$

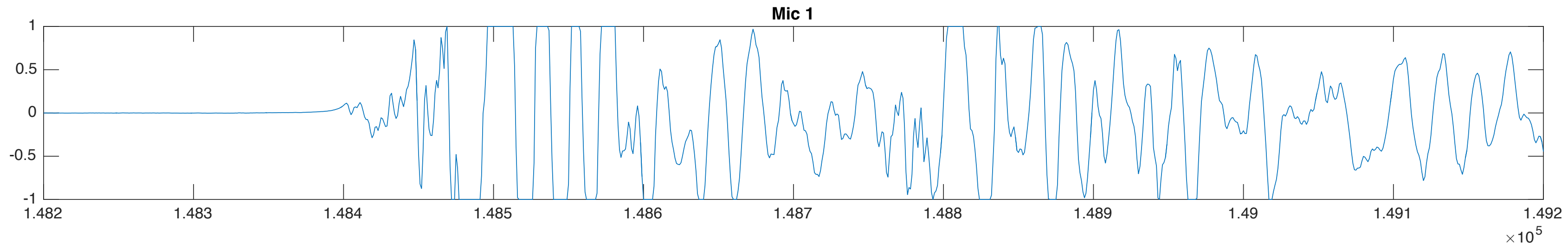




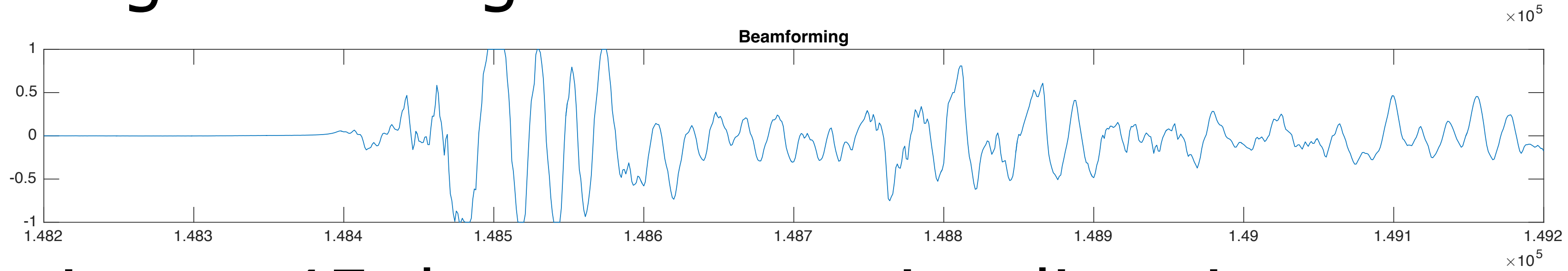

```
%reading audio files
file1 = 'TASCAM_0090S12.wav';
file2 = 'TASCAM_0090S34.wav';
[y,Fs]=audioread(file1);
ch0 = y(:,1);
ch1 = y(:,2);
[y,Fs]=audioread(file2);
ch2 = -y(:,1);
ch3 = -y(:,2);

range=1:80000;
x=(range);

subplot(4,1,1);
plot(x,ch0(range));
title('Mic 1');

ax = gca;
```

Beamforming Example

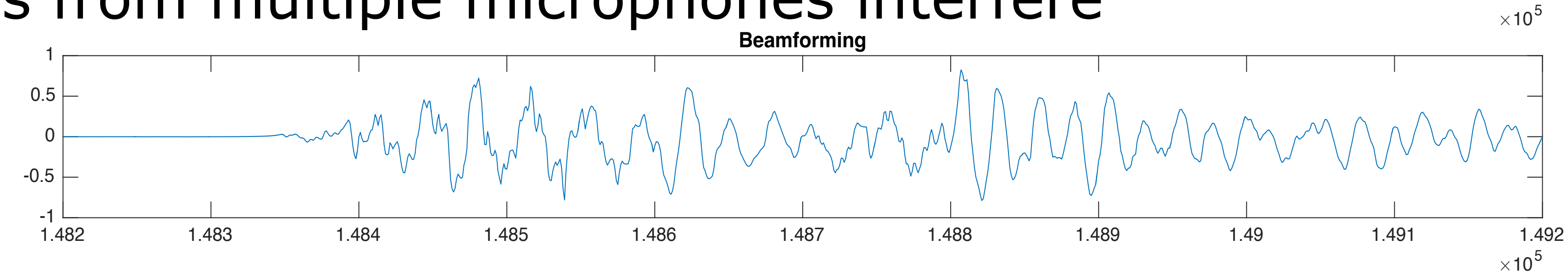
- Signal:



- Beamforming at 45 degrees toward mic 1:



- Beamforming at 45 degrees opposite direction:
  - Signals from multiple microphones interfere

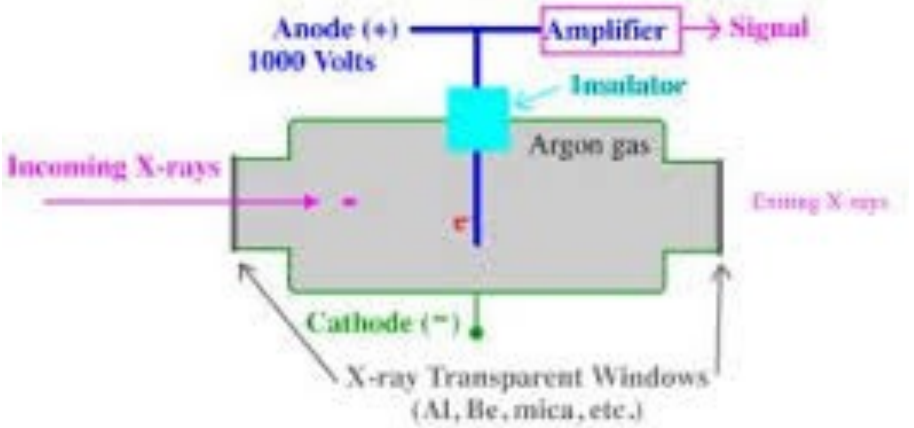


Medical Imaging

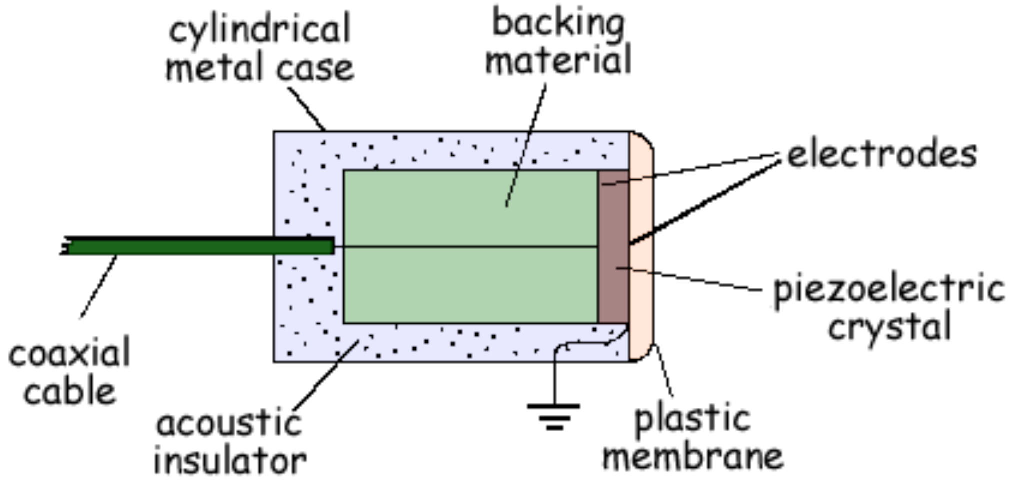
- Generation and interpretation visual representations of the human body
  - Anatomy (the structure of organs in the body)
  - Physiology (the functioning of organs)
- Key ECE contributions in medical imaging systems:
  - Sensors
  - Image computation
  - Image post processing

Medical Imaging: Sensors

- Transmission and detection of signals
- X-ray sources and detectors:

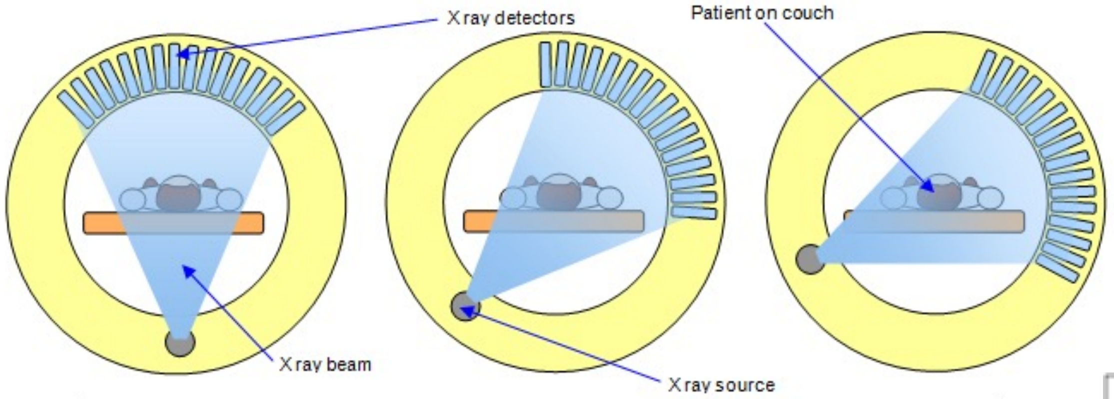


- Ultrasound transducers:

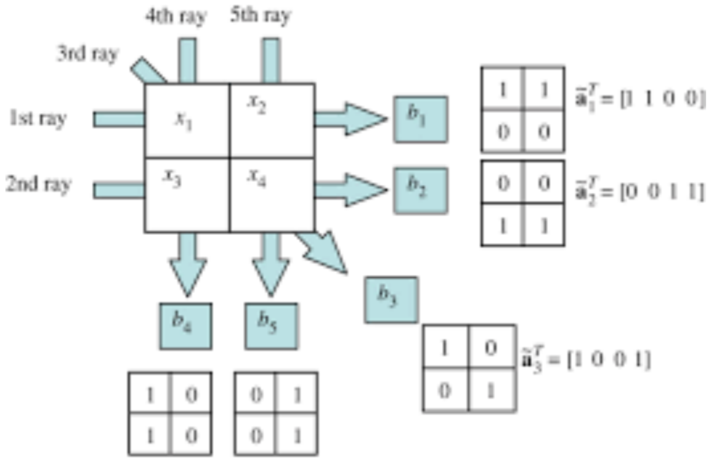


Medical Imaging: Image Computation

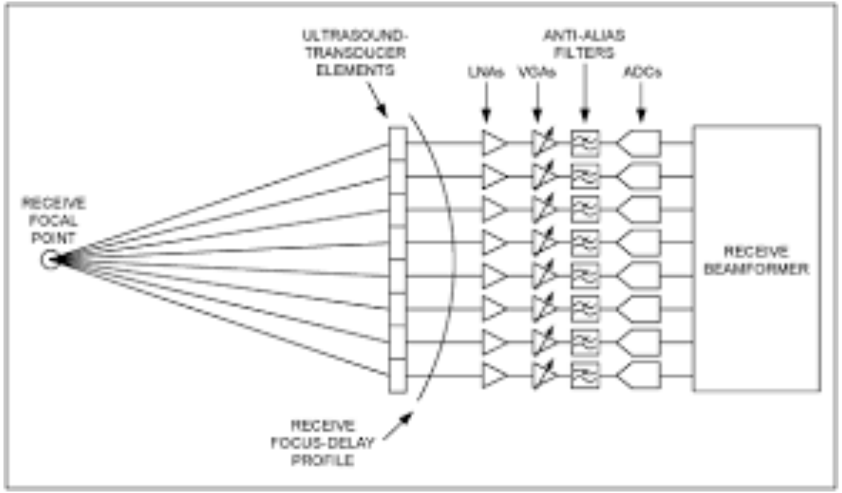
- Algorithms for displaying information from sensor as images
- X-ray computed tomography:



CT scanner with the X ray source and detectors shown in three positions



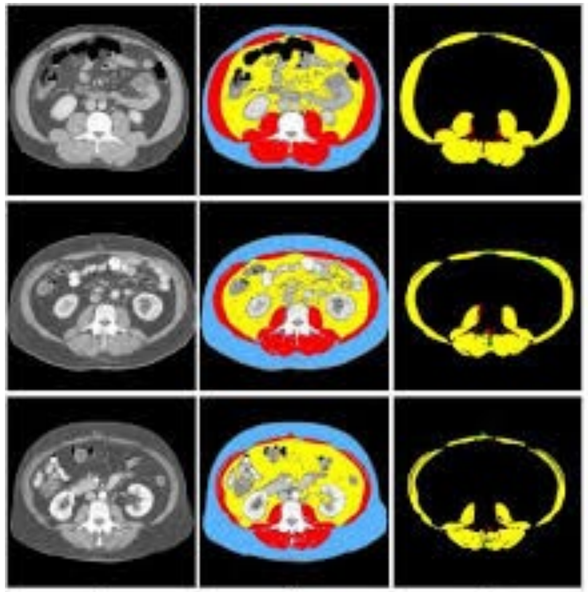
- Ultrasound beamforming:



From Maxim Integrated, Inc.

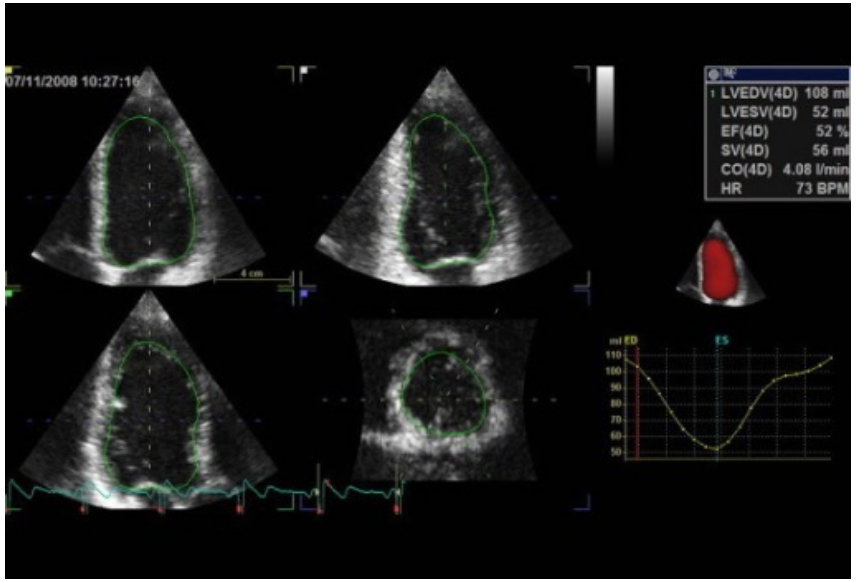
Medical Imaging: Image Postprocessing

- Extracting useful features or measurements from images
- Identifying tissue types:
  - X-ray



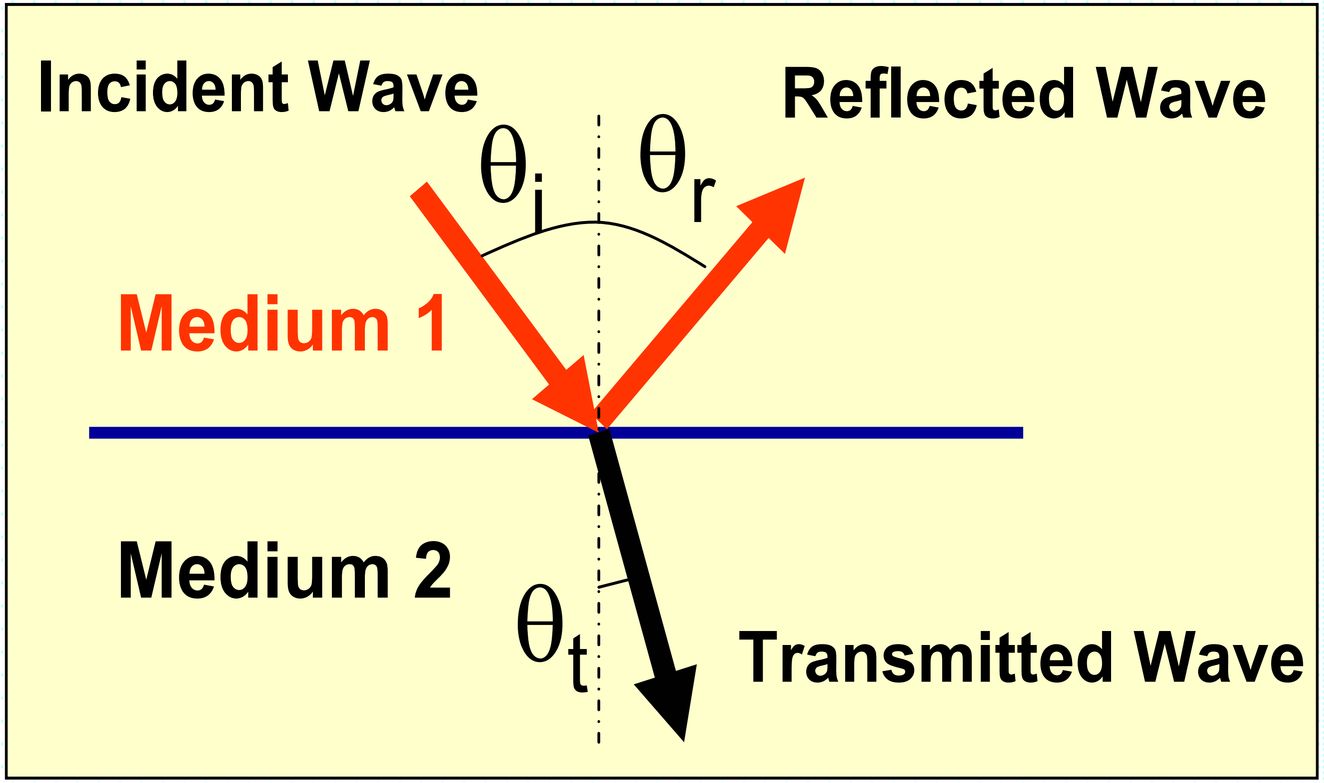
(a) (b) (c)

- Measuring cardiac output:
  - Ultrasound



Medical Ultrasound

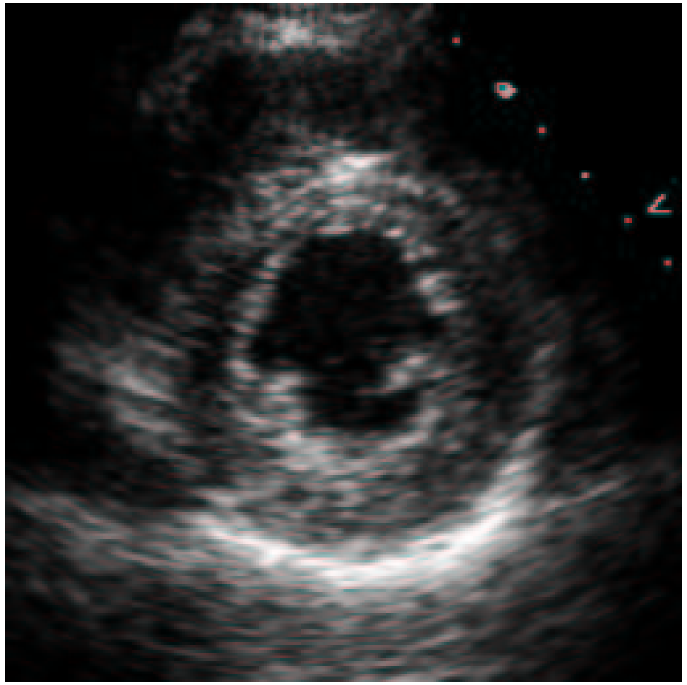
- Ultrasound frequencies: 1 MHz ~ 20 MHz
- Propagation of sound affected by tissue's acoustic impedance



Medical Ultrasound Frequency

- Reflections occur when regions are larger in size than the wavelength of the ultrasound signal
  - Wavelength:

$$\lambda = \frac{c_s}{f}$$



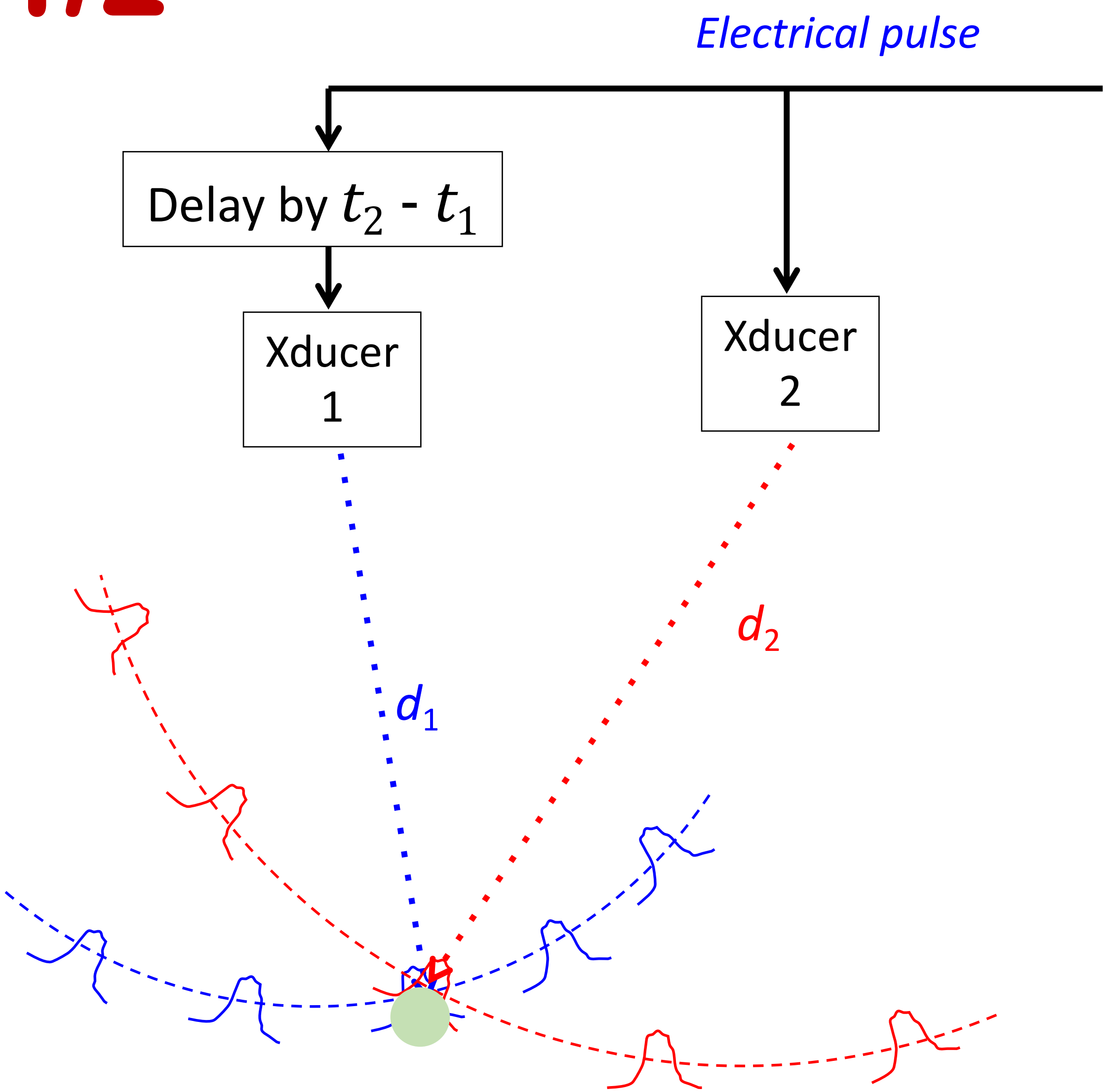
- The speed of sound in tissue is 1540 m/sec
- To see 1 mm objects

$$\lambda < 0.001\ \mathrm{m} = \frac{1540\ \mathrm{m/sec}}{f\ \mathrm{Hz}}$$

$$f > 1.54 \times 10^6\ \mathrm{Hz} = 1.54\ \mathrm{MHz}.$$

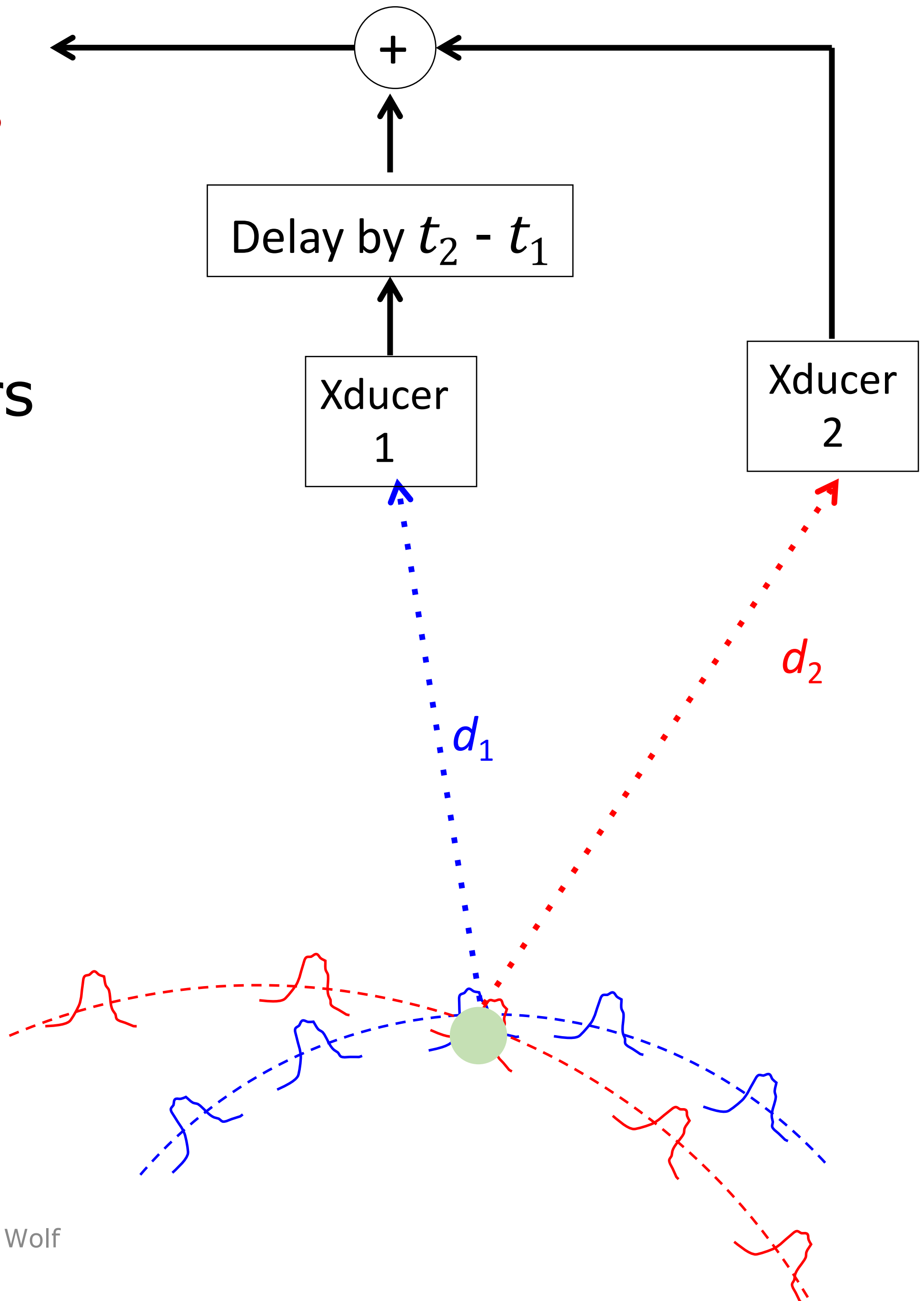
Ultrasound System 1/2

- Multiple transducers
  - Transmit ultrasound energy
- Energy can be focused
  - Delay between transmissions of different transducers
  - Beamforming



Ultrasound System 2/2

- Receive beamforming
  - "Listening" in a particular direction
  - Delay between different transducers

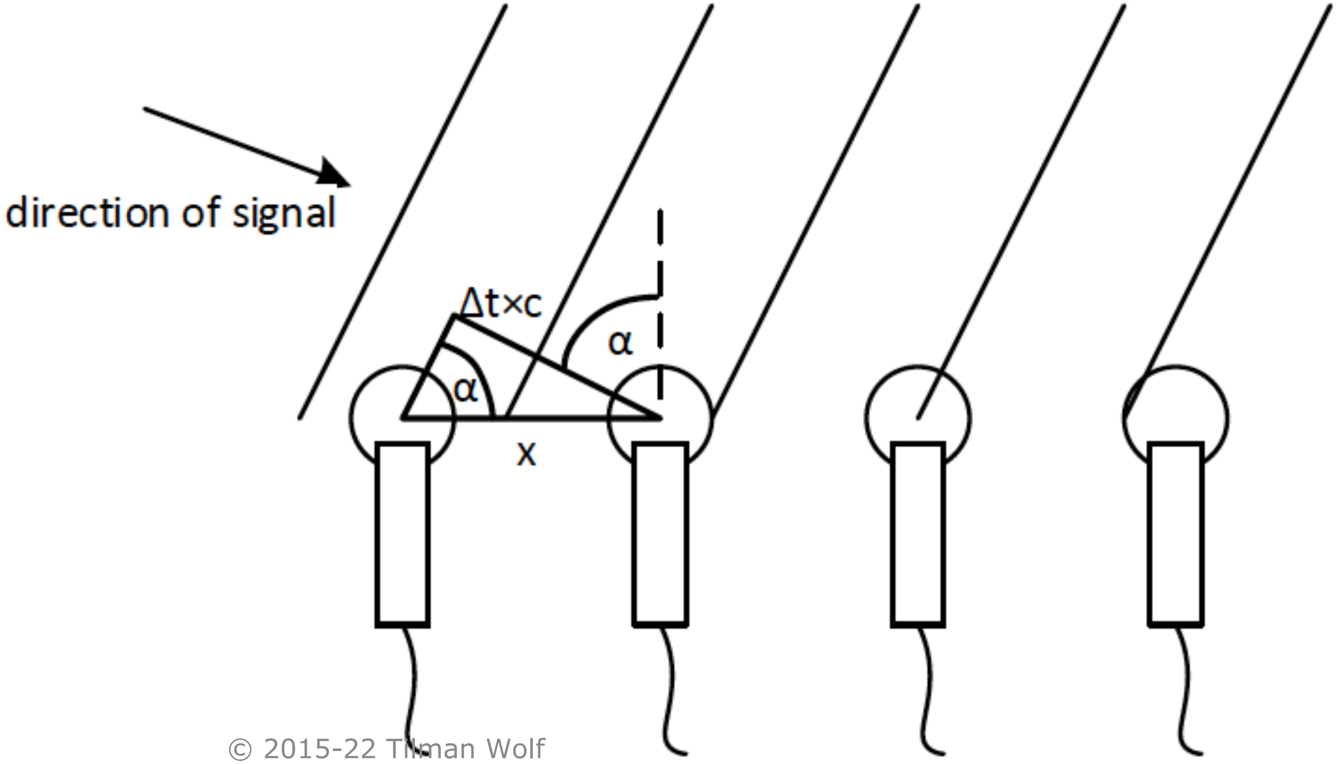


Beamforming Again…

- Determine angle of arrival based on signal delay
  - Distance between microphones x
  - Signal propagation speed c
  - Arrival delay Δt
  - Angle of arrival α
- Utilize rectangular triangle property:

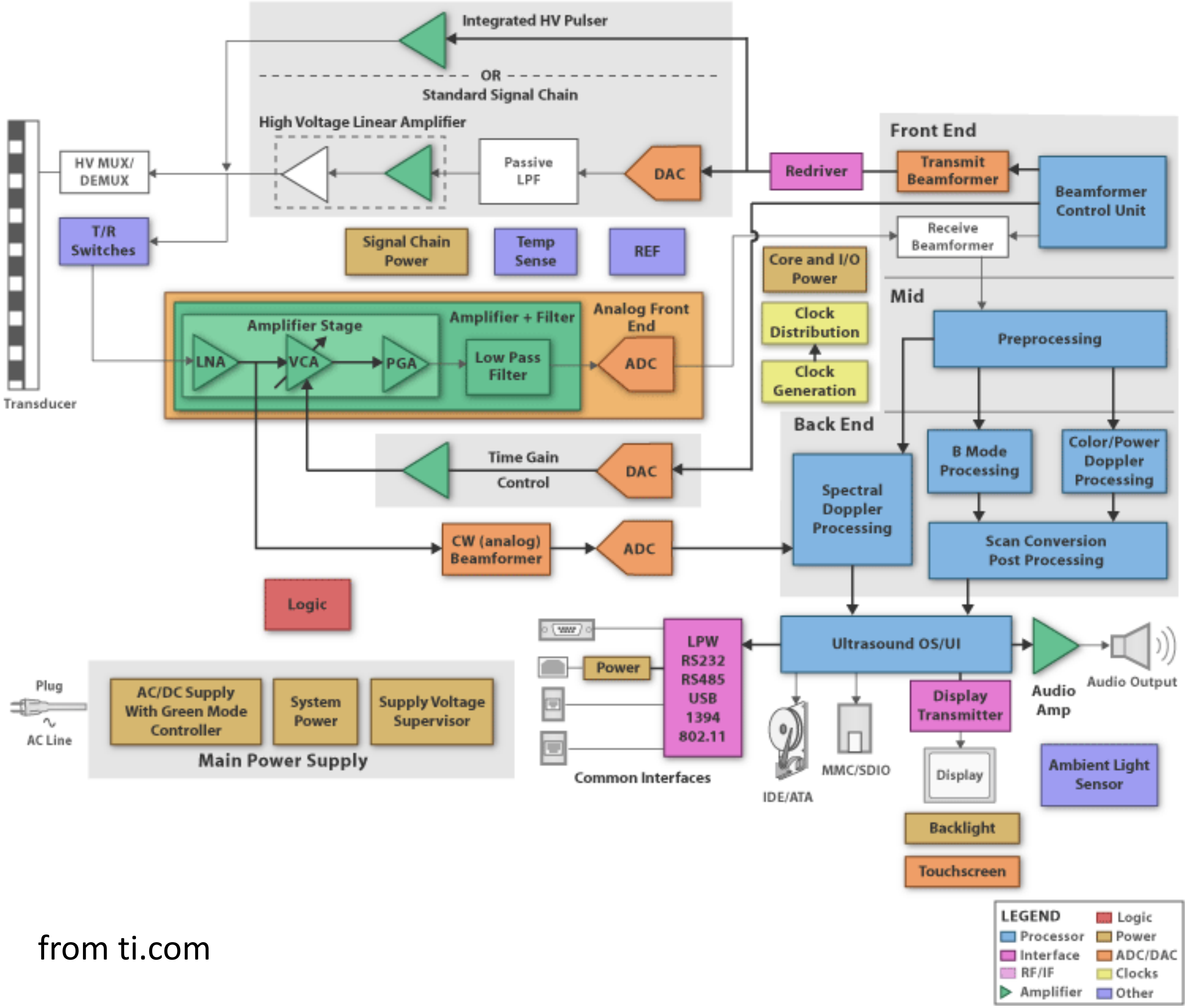
$$\sin\alpha = \frac{\Delta t \times c}{x}$$

- Same as before…



Ultrasound

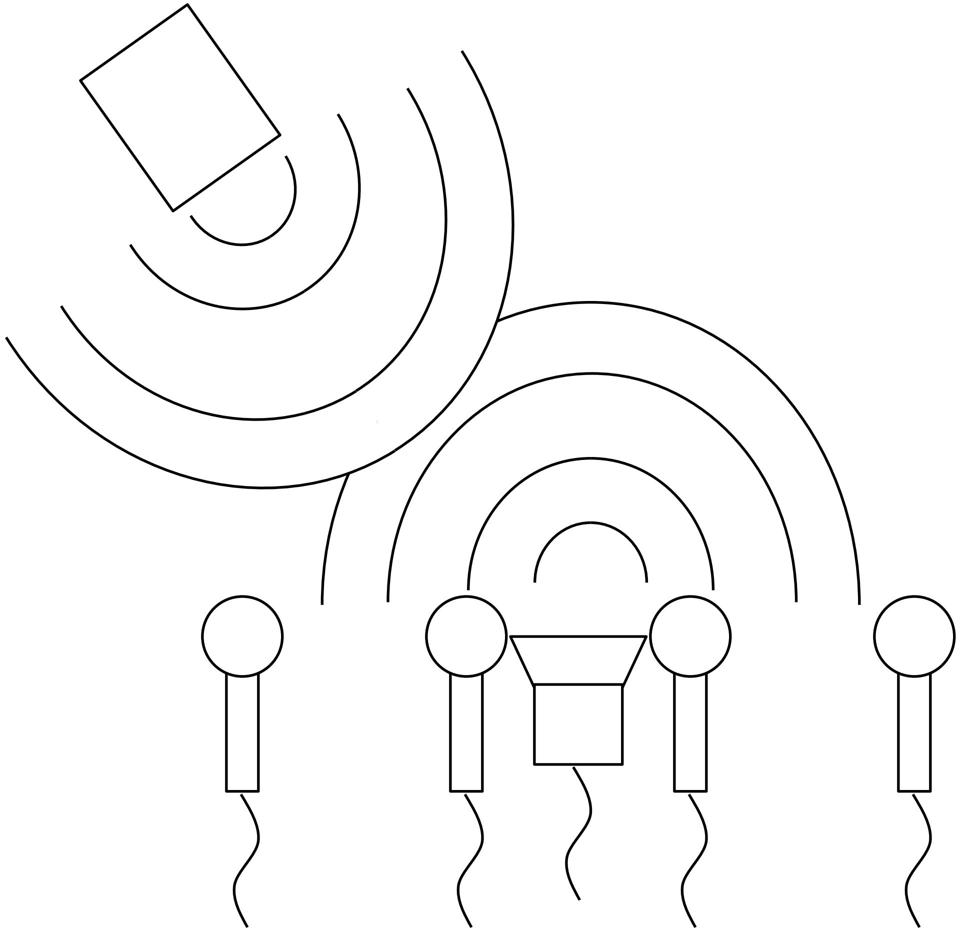
- System diagram:
  - Beamforming
  - Transducers transmit and receive
- Practical system is much more complex
  - We focus on principles
- Data rates very high
  - 64 transducers sampling at 40 MHz with 12-bit quantization (72 dB): 3.84 GB/s



from ti.com

Ultrasound Demo Setup

- Sensing environment through echolocation



Summary

- Location is important for many systems
- Relative positioning is often used
- Measurements are often afflicted with errors
  - Dead reckoning accumulates error
- Absolute positioning (latitude/longitude)
- Accurate time is critical for longitude
  - Precise clocks or lunar distance method
- GPS uses synchronized time signal from multiple satellites
- Signal propagation delay is important
  - Distance and angle measurement
  - Application in ultrasound medical imaging