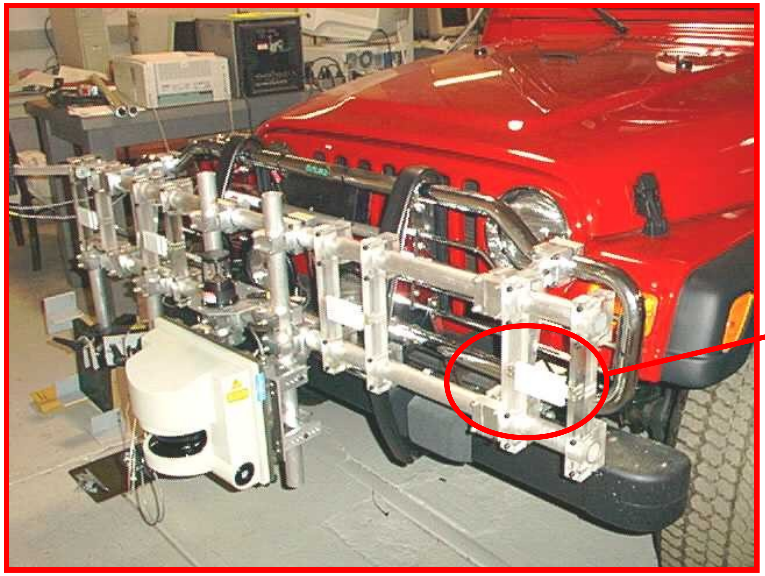
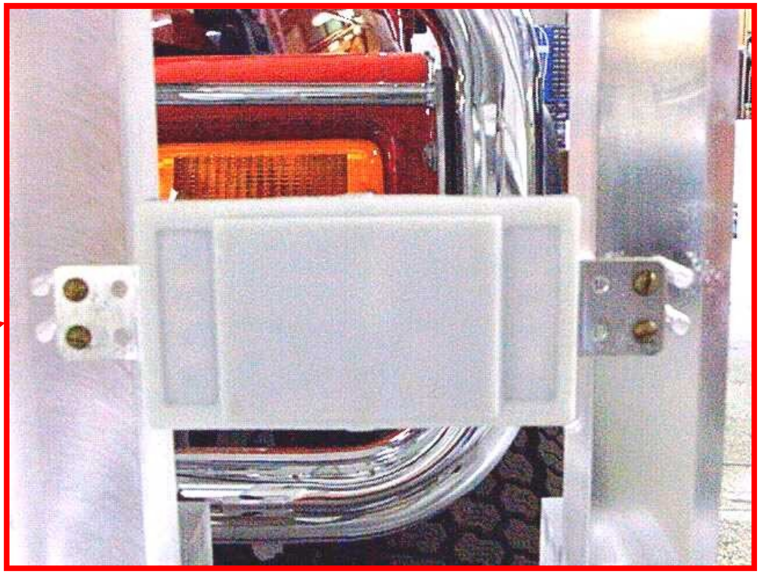
echo-based range sensing

example: low-cost radar

- automotive DC in / digital radar signal out
- applications include
  - pedestrians / bicycles in urban environment
  - obstacles / vehicles in highway environment
  - smart cruise control





echo-based range sensing

- general principles
  - lidar / ladar
  - radar
  - ultrasound
  - etc
- contrasting implementations

rangefinder goal

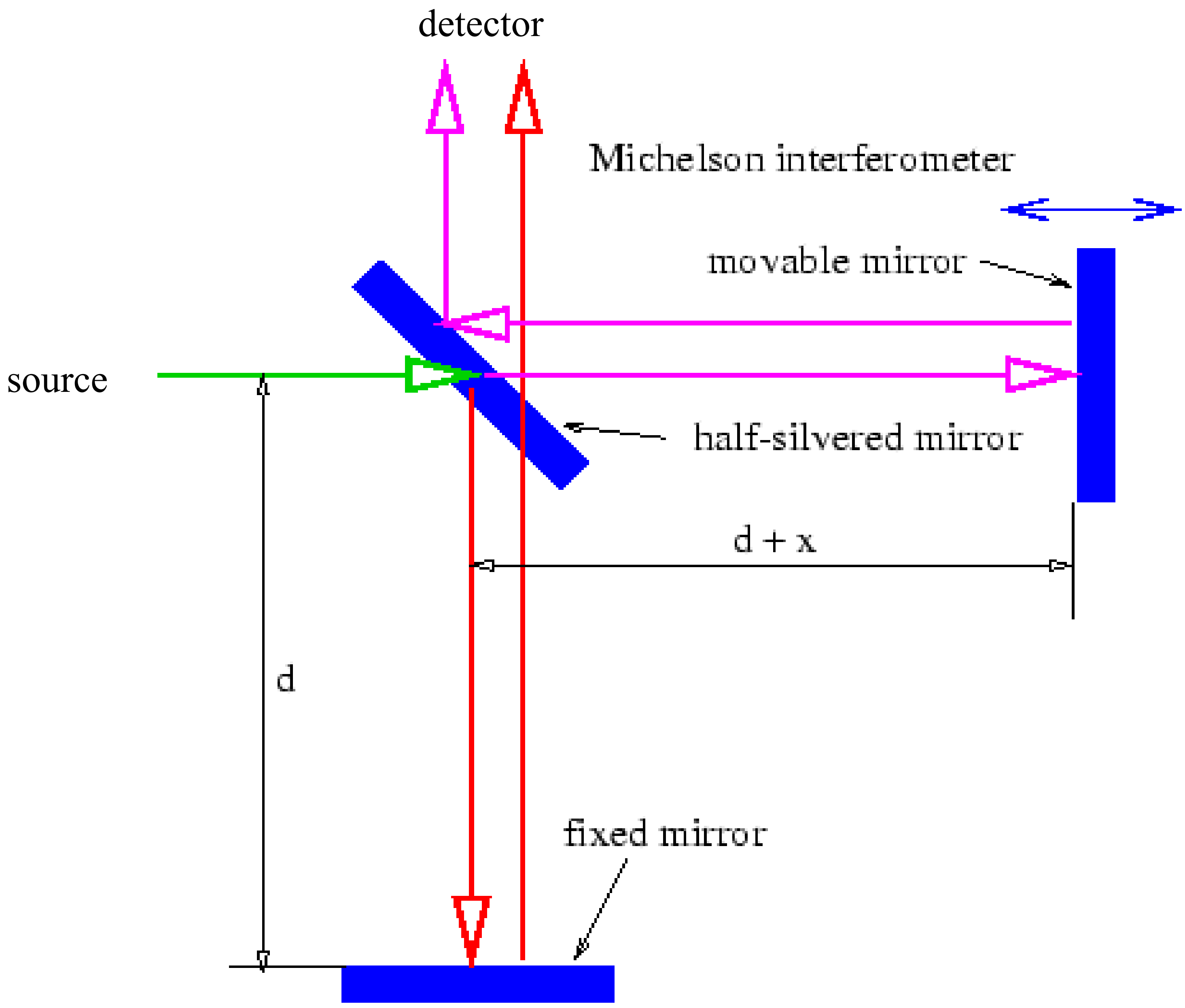
- measure the distance to a “target”
  - something like an obstacle in the roadway

by observing how changes in distance cause changes in a measurable property of {light, sound, radio waves} that travel to and from the target

- properties commonly measured:
  - phase of the optical radiation (near)
  - phase of an imposed modulation (middle)
  - time-of-flight (far)

optical phase

- principle is *interference* of a wave that is split in two, travels two different paths, and are then recombined with a time-of-flight difference between them
- used mostly in extremely high precision measurements of very small distances
  - as in machining of very precise parts
- not typically used in robotics applications

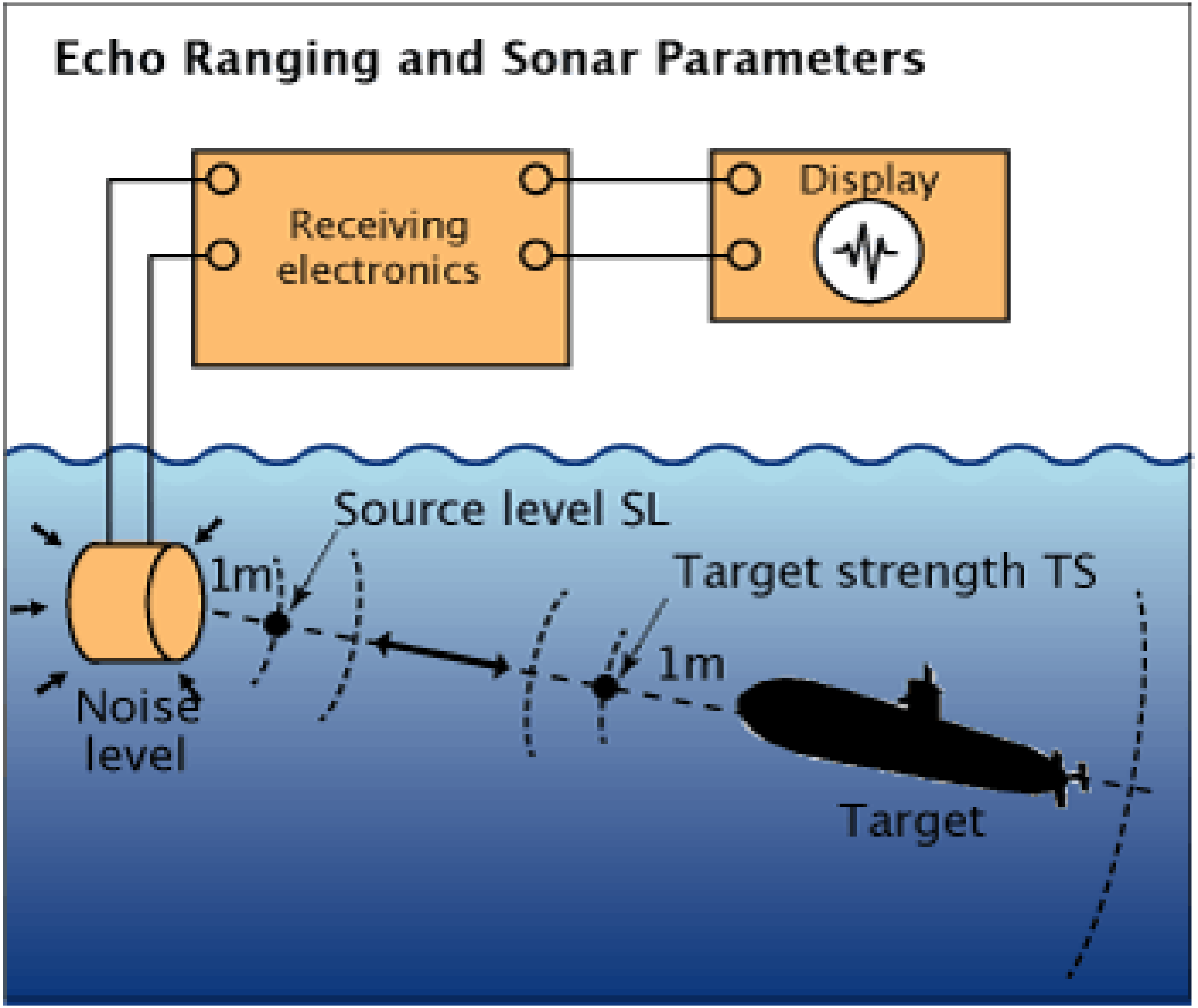

detector
Michelson interferometer
movable mirror
source
half-silvered mirror
d + x
d
fixed mirror

exercise – not assigned now

- suppose the detector in the Michelson interferometer (previous slide) is a CCD
  - what would the image look like when the path difference is between the split beams is an integral number of wavelengths?
  - ½ + integral number of wavelengths?
  - somewhere in between?
  - is there any limit to how big the integer can get before the simple explanation fails and you need to understand more to explain it?

time-of-flight (ToF)

- measure the time to "see" or "hear" echo
- range (distance): z = c t / 2
  - t = ToF from source to target back to sensor
  - ½ assumes source & sensor are in same place
- light: $c \approx 3 \times 10^{8}$ m s^{-1}
  - in vacuum
  - slower by factor ≈ 1.33 in water, ≈ 1.5 in glass
- radio waves (radar) same as light
- sound (sonar): $c \approx 343$ m s^{-1}
  - in air at normal temperature
  - ≈ 1500 m s^{-1} in water at normal temperature


Echo Ranging and Sonar Parameters
Receiving electronics
Display
Source level SL
Target strength TS
1m
1m
Noise level
Target

exercise – not assigned now

- On an early moon landing an astronaut set up a panel with about ½ m^2 of corner cube reflectors. A pulsed laser was aimed at it from earth, and the earth-moon distance thereby measured to high precision. Estimate the ToF between transmitted and received laser pulses. If the laser beam spreads to 1 mile diameter at the moon and the return beam – also spread to about 1 mile diameter on earth – is captured by a 100-inch-diameter telescope, how much energy do you need in each laser pulse to average one detected photon from each pulse? Don't forget to state your assumptions! [FYI, I think all these numbers are the right order-of-magnitude except for the return beam diameter on earth, which I don't actually remember; extra credit if you can find and use it!]

is ToF easy or hard to measure?

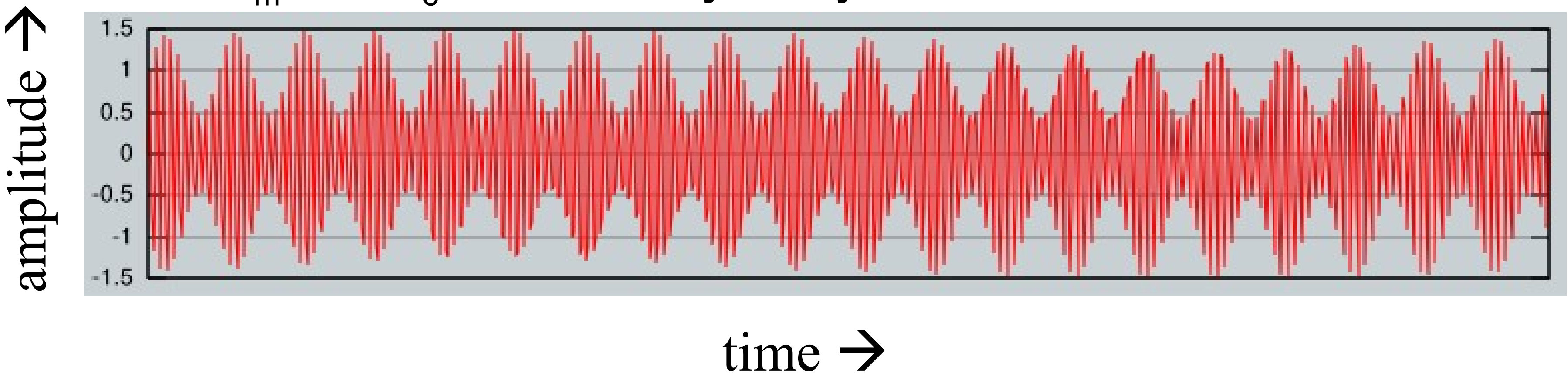
- velocity of sound is small enough that it is *easy* to measure ToF directly (sonar)
- velocity of light (and radio) is big enough that it is *hard* to measure ToF directly
  - unless the range is large, i.e., more that 1 km
  - so for short-range ranging with light (lidar) or radio (radar) we measure ToF indirectly
    - i.e., we use the phase of the modulation

modulation phase

- $\Phi_c = 2\pi\, x / \lambda_c$
  - x = path difference, λ_c = wavelength of light or radar
  - difficult to measure Φ_c unless $x < \lambda_c$
- use the light or radar as a *carrier* for a lower frequency (→ longer wavelength) modulation that changes slowly compared to the fast rate-of-change of $\sin(2\pi f_c t)$
- it is relatively easy to measure how the *phase of the modulation* changes with path difference

modulation option 1

- AM (amplitude modulation, but really intensity modulation): $M(t) = A_0 \sin(2\pi f_m t)$
  - measure phase shift of echo relative to transmission:
    $A_0 \sin(2\pi f_m t) \rightarrow A_1 \sin(2\pi f_m t + \Phi_m)$
    $\Phi_m = 2\pi x / \lambda_m$
    $(\lambda_m = c / f_m) >> (\lambda_c = c / f_c)$
    so $\Phi_m << \Phi_c$ is relatively easy to measure

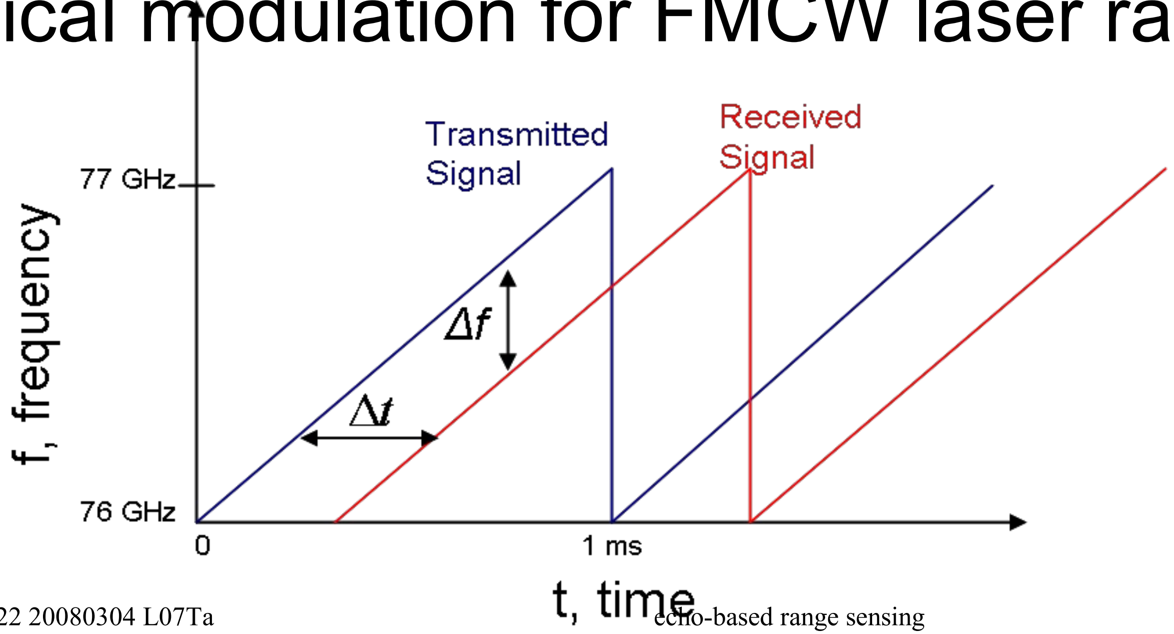


modulation option 2

- FM (frequency modulation):
  $M(t) = A_0 \sin(2\pi f_c (1 + A_m \sin 2\pi f_m t) t))$
  - FM radio signal: tone at frequency f_m

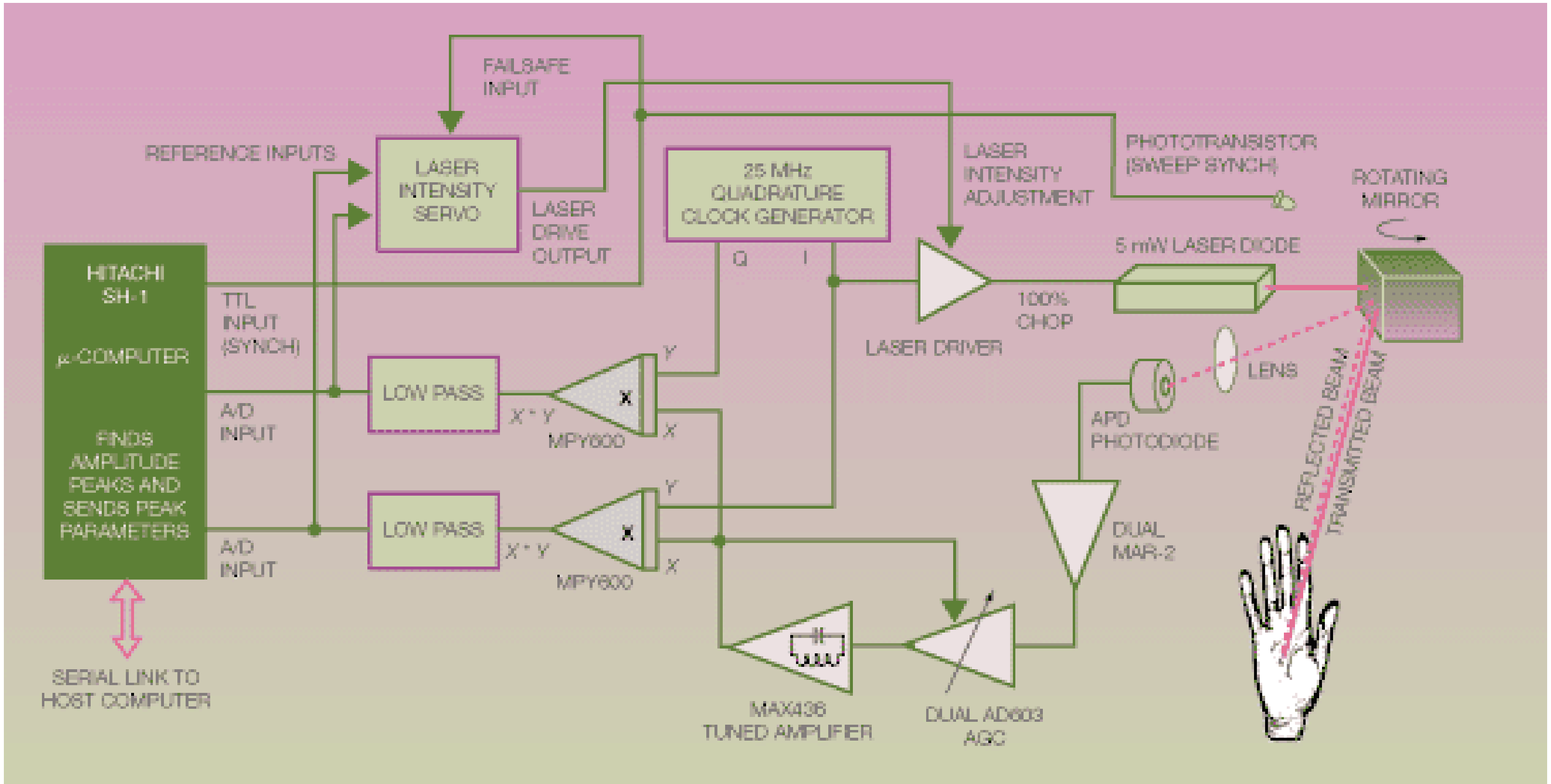
$M(t) = A_0 \sin(2\pi f_c (1 + A_m \text{ sawtooth}(t) t))$

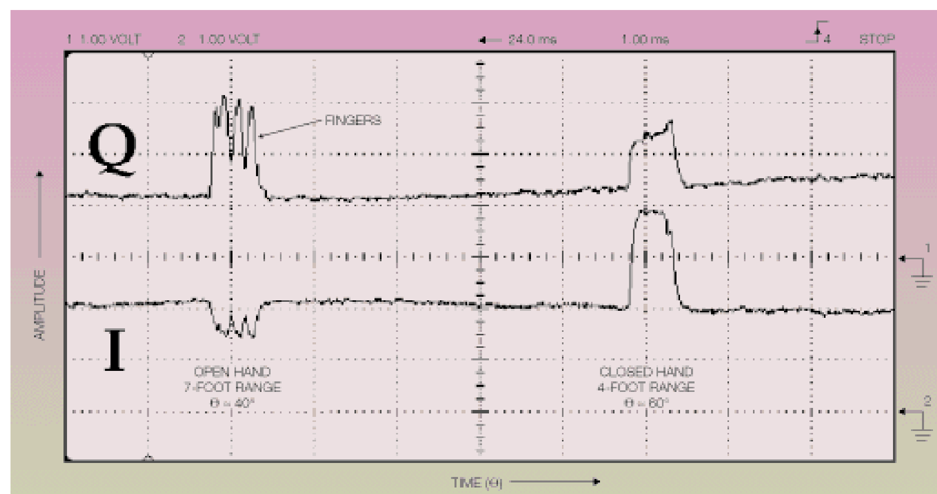
- typical modulation for FMCW laser rangefinder



electronics for AM detection

- phase sensitive amplifier
- generally two channels:
  - modulation ~ sin(ωt)
  - one channel reference (“I”) ~ sin(ωt)
  - second channel reference (“Q”) ~ cos(ωt)
  - $\Phi = \arctan(\text{Signal}_Q/\text{Signal}_I)$
    - maybe do the arithmetic digitally …
    - but possibly better to do it by analog computing
      - something like $\arctan[\exp[\ln[\text{Signal}_Q]-\ln[\text{Signal}_I]]]$ implemented in components with nonlinear I vs. V


FAILSAFE
INPUT
REFERENCE INPUTS
LASER
INTENSITY
SERVO
LASER
DRIVE
OUTPUT
25 MHz
QUADRATURE
CLOCK GENERATOR
LASER
INTENSITY
ADJUSTMENT
PHOTOTRANSISTOR
(SWEEP SYNCH)
ROTATING
MIRROR
5 mW LASER DIODE
HITACHI
SH-1
μ-COMPUTER
FINDS
AMPLITUDE
PEAKS AND
SENDS PEAK
PARAMETERS
TTL
INPUT
(SYNCH)
Q
I
100%
CHOP
LASER DRIVER
LENS
A/D
INPUT
LOW PASS
X * Y
MPY600
Y
X
APD
PHOTODIODE
REFLECTED BEAM
TRANSMITTED BEAM
LOW PASS
X * Y
MPY600
Y
X
A/D
INPUT
DUAL
MAR-2
SERIAL LINK TO
HOST COMPUTER
MAX436
TUNED AMPLIFIER
DUAL AD603
AGC


1 1.00 VOLT
2 1.00 VOLT
24.0 ms
1.00 ms
STOP
Q
FINGERS
AMPLITUDE
I
OPEN HAND
7-FOOT RANGE
θ ≈ 40°
CLOSED HAND
4-FOOT RANGE
θ ≈ 60°
TIME (θ)

exercise – not assigned now

- A green laser, wavelength 488 nm, is (amplitude) modulated at 10 MHz. For a target at 100 m range, what is the phase shift of the return signal relative to the transmitted signal and the ratio $Signal_Q/Signal_I$. What is n, the phase ambiguity in modulation wavelengths?
- Show that if you change the wavelength a small known amount and measure again you can resolve the ambiguity.

electronics for FM detection

- option 1: simple “mixer”:
  - combine a sample of the currently transmitted signal and the (delayed) received signal using a non-linear amplifier
  - low frequency signal appears at the difference frequency (→ range)
- $(A \sin(2\pi f_{transmitted} t) + B \sin(2\pi f_{received} t))^2$
  upon expansion, trigonometric identities reveal a term proportional to
  $\sin(2\pi (f_{transmitted} - f_{received}) t)$

electronics for FM detection

- option 2: FFT module
  - record the echo vs. time
  - digitize it
  - perform an FFT
  - intensity at each frequency corresponds to echo strength at corresponding distance

exercise – not assigned now

- Using the green laser from your AM laser rangefinder to build an FM laser rangefinder, what frequency slew rate (Hz/second) would you need to observe a difference frequency of 10 kHz when the target range is 100 m?
- Is there an ambiguity problem with FM modulation? (explain!)