sound & tactile sensing

why combine tactile & sound sensors?

- applications are very different
- but both are (usually) *pressure* transducers
- big difference is the frequency range
  - pressure: DC - ~1 Hz
  - tactile: ~ 0.1 Hz - ~ 1000 Hz
  - sound: ~10 Hz - ~ 10 MHz (or more)
- typical devices are electromechanical
  - similar – or the same – transducer
    is used as both the transmitter & the receiver

- pressure is force per unit area
- almost all force – or pressure – sensing technologies involve …
  - a mechanical deformation under load
  - transduction-to-electrical to measure it
- the main exception is for measuring gas pressure under near-vacuum conditions
  - then it is typically done at a microscopic level
    - cooling rate of an electrically heated filament
    - ion current produced by an electron current
    - drag on a magnetically-suspended rotor
  - these are really *density* measurements, translated into pressure via $P V = n R T$

reading (Fraden)

- Section 3.10, Sound
  - understand Equation 3.105
  - be happy with Table 3.3
- Section 6.1, Ultrasonic Sensors
- Section 7.6, Ultrasonic Sensors
- Chapter 9, Force, Strain, Tactile
- Chapter 10, Pressure
- Chapter 12, Acoustic

topics we will cover

- the jargon of sound measurement (briefly)
- wave packets & consequent issues
- matched filter determination of ToF
- problem: beam width & specular reflection
- survey of sonar transducers
- the “strange” behavior of piezoelectrics
- a little about ultrasonic electronics modules
- issues in quantitative ultrasonic imaging
- tactile sensors & displays
  - (if not covered in a future student lecture)

the jargon of sound measurement

sound pressure level (SPL)

- “threshold of audibility”, the minimum pressure fluctuation detected by the ear, is less than 10^{-9} of atmospheric pressure or about 2×10^{-5} n/m^2 at 1000 Hz
- “threshold of pain”: pressure 10^5 times greater (still less than 1/1000 of atmospheric pressure)
- because of the wide range, sound pressure measurements are made on a logarithmic (decibel) scale
- “sound pressure level” (SPL) $= 20 \log(P/P_0) = 10 \log(P/P_0)^2$, where $P_0 = 2 \times 10^{-5}$ newton/meter^2
  - because energy and power scale as pressure squared
  - *caution: pay attention to when P = pressure and when P = power*
- SPL is proportional to the average squared amplitude

sound power (SP & PWL)

- SP = total sound power W emitted by a source in all directions
  (in watts = joules/second)
- sound power level
  PWL = 10 log(W/W_0) deci**b**els
  - where $W_0 = 10^{-12}$ watt (by definition)
- = 10 log$(P/P_0)^2$ deci**b**els
  = 20 log(P/P_0) deci**b**els

in terms of pressure

sound intensity level (IL)

- rate of energy flow *across unit area*
- sound intensity level

  $IL = 10 \log(I/I_0)$

  - where $I_0 = 10^{-12}$ watt/meter^2

multiple sources

- two equal sources produce a 3 dB increase in sound power level
  - because $\log_{10}2 = 0.301029996$

    $10 \log_{10}2 \approx 3$
- two equal sources produce a 3 dB increase in sound pressure level (assuming on average no interference,
  i.e., incoherent random phases)
- for example, when two 80 dB SPL sources add the result is an 83 dB SPL
  (assuming they are incoherent)

tying all these & more together …

- see http://en.wikipedia.org/wiki/Sound_energy_density

$$E = \xi^2 \cdot \omega^2 \cdot \rho = v^2 \cdot \rho = \frac{a^2 \cdot \rho}{\omega^2} = \frac{p^2}{Z \cdot c} = \frac{I}{c} = \frac{P_{ac}}{c \cdot A}$$

where:

Symbol	Units	Meaning
p	pascals	sound pressure
f	hertz	frequency
ξ	m, meters	particle displacement
c	m/s	speed of sound
v	m/s	particle velocity
$\omega = 2 \cdot \pi \cdot f$	radians/s	angular frequency
ρ	kg/m^3	density of air
$Z = c \cdot \rho$	N·s/m^3	acoustic impedance
a	m/s^2	particle acceleration
I	W/m^2	sound intensity
E	W·s/m^3	**sound energy density**
P_{ac}	W, watts	sound power or acoustic power
A	m^2	area

exercise

An acoustic sensor, in the absence of any signal of interest, outputs an RMS noise level of 500 μV. When an acoustic signal of interest is added, the sensor's RMS output becomes 1300 μV. What is the signal-to-noise power ratio expressed in decibels? What would it be if the sensor's RMS output were to become 2 V when signal of interest is added? [Note: be careful about (1) how RMS quantities add (2) the distinction between signal-to-noise and (signal+noise)-to-noise]

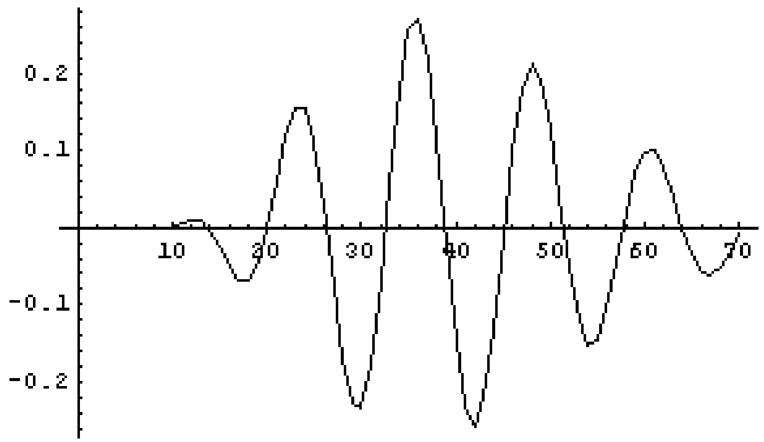
ranging by wave packet ToF

- emit a pulse of acoustic energy
- detect its echoes from nearby objects
- measure the time-of-flight (ToF) of each
- multiply by speed-of-sound to get ranges
- issues:
  - directionality: which object at which azimuth
  - signal diminishes with range
    - spreading: energy density decrease ($1/z^2$)
      - all waves diminish as $1/z^{(\text{dimensionality\_of\_space} -1)}$
    - attenuation: energy loss to heat (exponential)
      - inherent in nature of sound (but not light)

the "wave packet" concept

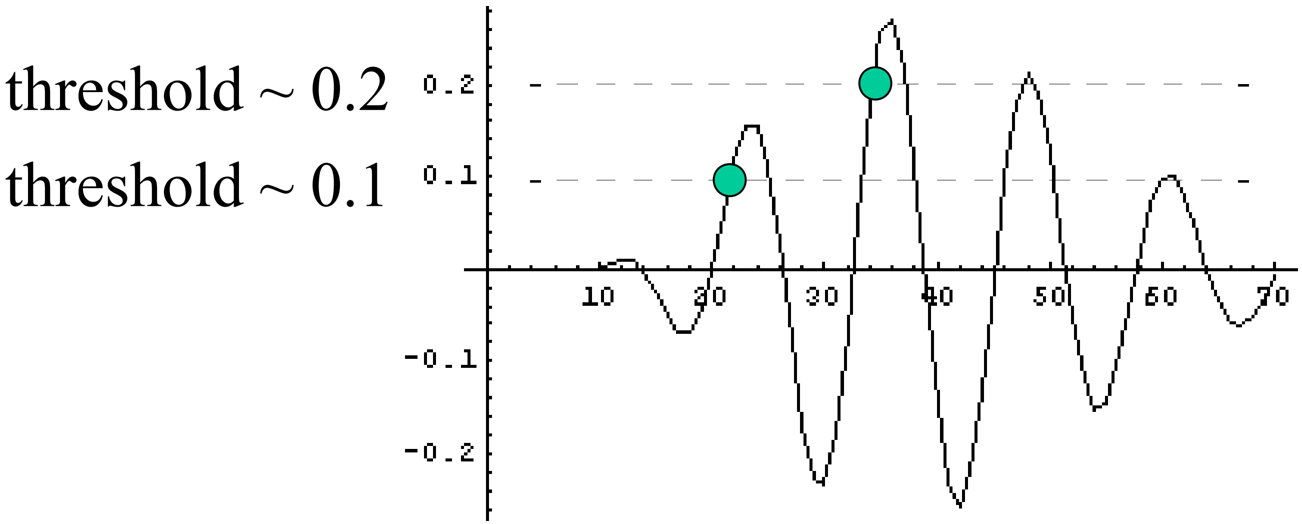
- a "wave packet" is a finite-duration burst of transmitted energy (acoustic, light, etc)
  - τ measures its duration
  - t_o measures its mean time
  - often it is – or is approximated as – Gaussian:

$$A(t) = A_o \exp[-((t-t_o)/\tau)^2] \cos(2\pi f (t-t_o))$$



problem: range jumps

- cheap systems commonly detect the time of echo amplitude crossing a threshold



solution: matched filter

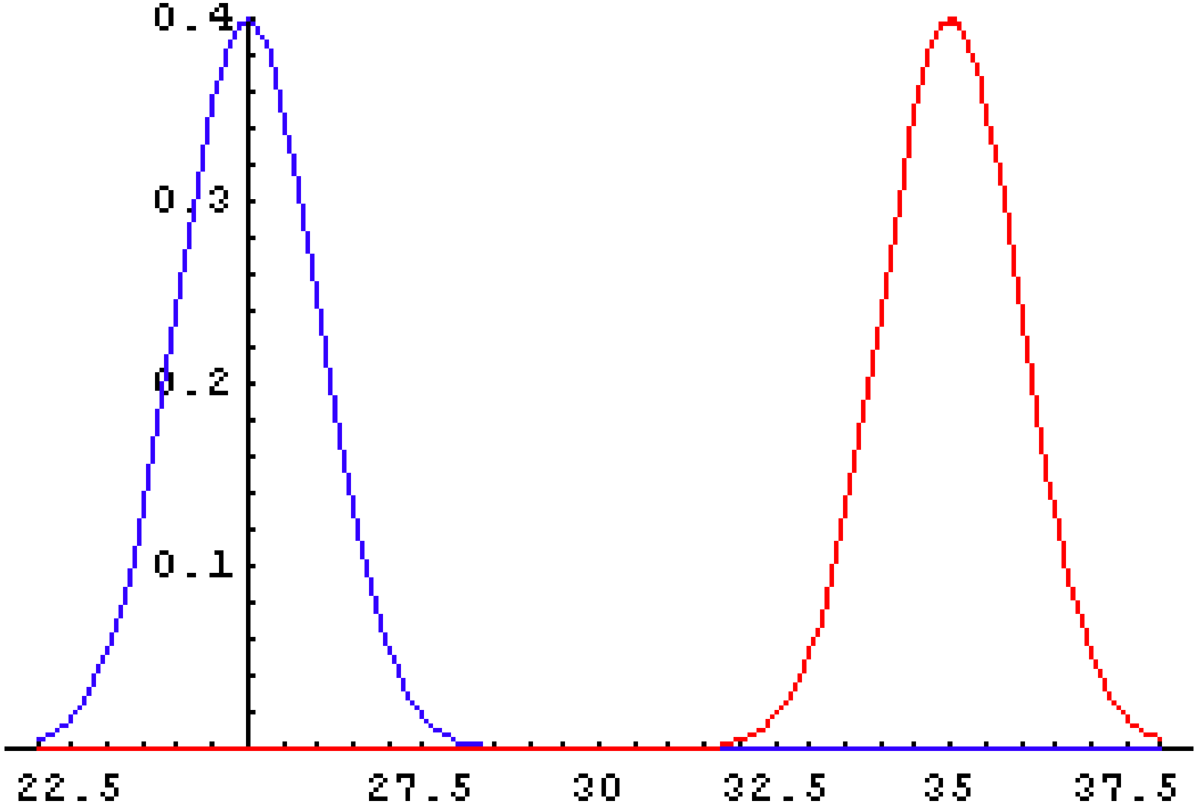
- correlate incoming signal with its expected shape, i.e., the shape of the outgoing pulse
- *but it's not quite as easy as you would like: <u>dispersion</u> and differential <u>attenuation</u> distort the echo vs. the outgoing pulse*
  - *dispersion: velocity depends of frequency*
    - issue for sound *and* for light *in a medium*
  - *differential attenuation: amplitude decay per unit distance covered depends on frequency*
    - this is the energy dissipation phenomena, not the universal geometrical spreading

nevertheless,
here is a seat-of-the-pants
picture of how
matched filters work

envelopes of pulse and echo

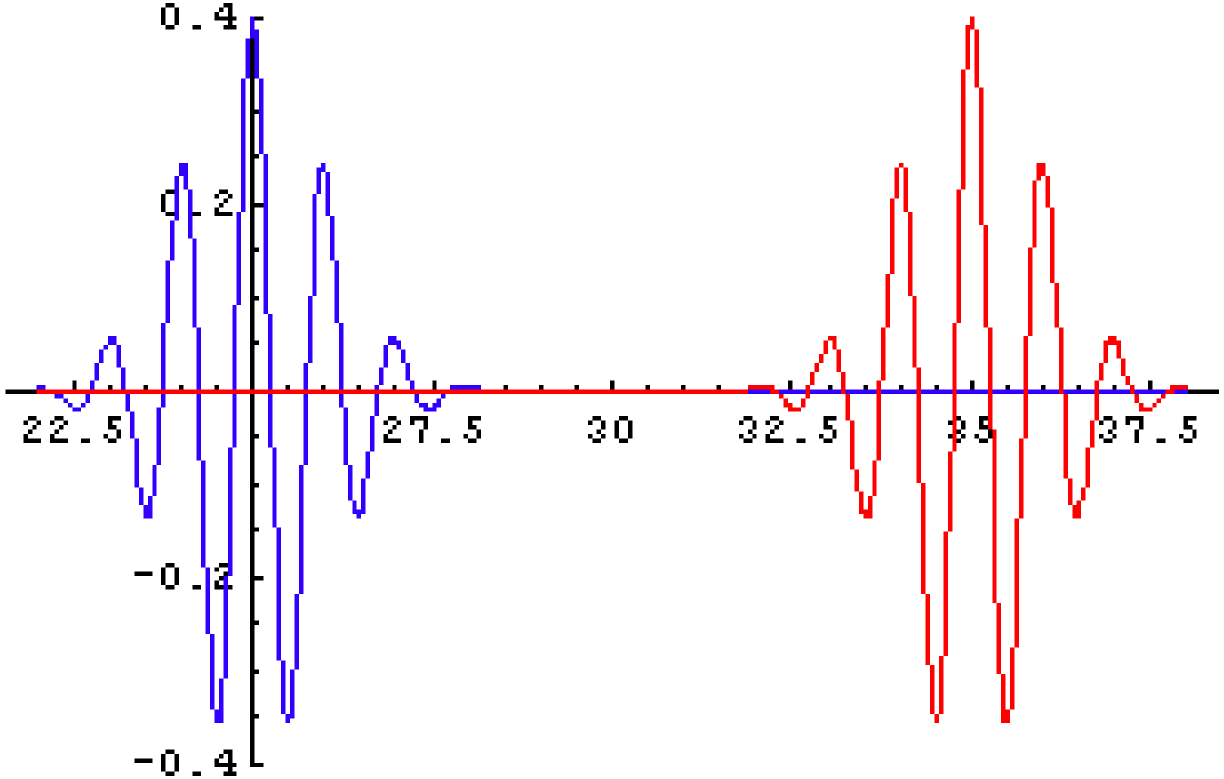
```
gauss[t_, t0_, ts_] := (1/Sqrt[2 Pi] ts) Exp[-(t - t0)^2/(2 ts^2)]
```

```
Plot[{gauss[t, t0, ts], gauss[t, t0 + tof, ts]}, {t, t0 - 3. ts, t0 + tof + 3. ts}, PlotStyle → {Hue[.7], Hue[.0]}, PlotRange → {0, .4}] /.
 {t0 → 25., ts → 1., tof → 10.}
```



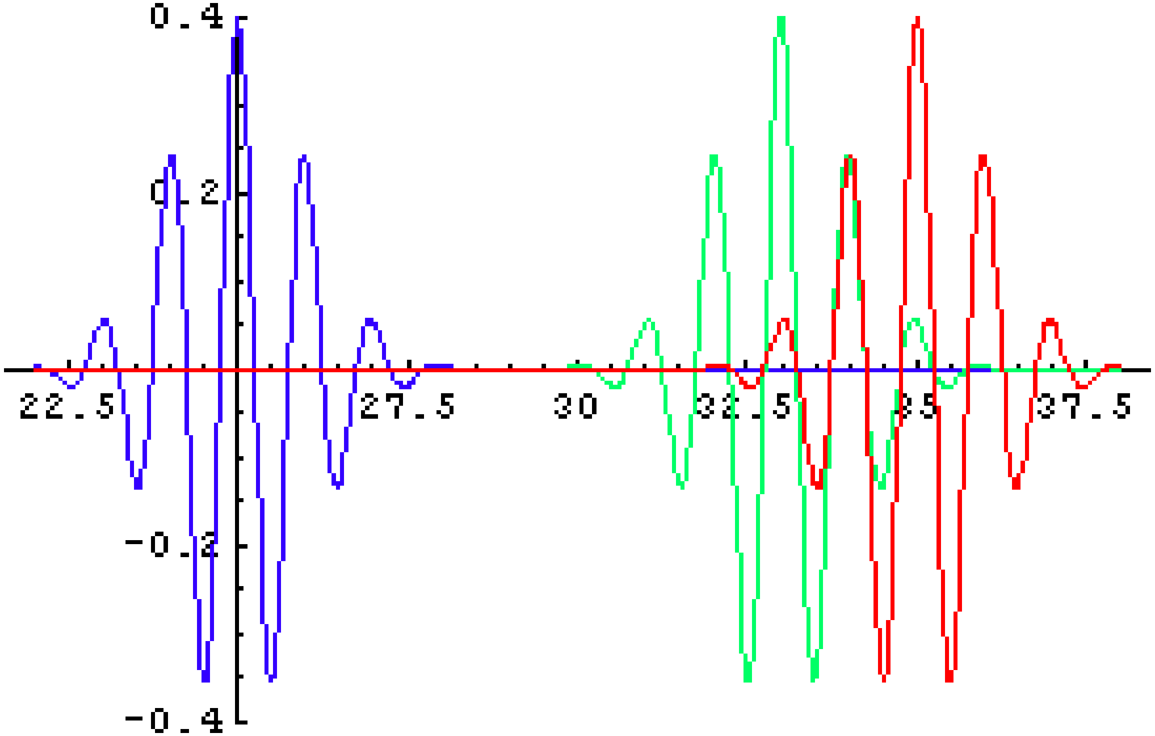
underlying ultrasonic oscillation

```
Plot[{gauss[t, t0, ts] Cos[2 Pi f (t - t0)], gauss[t, t0 + tof, ts] Cos[2 Pi f (t - (t0 + tof))]} , {t, t0 - 3. ts, t0 + tof + 3. ts},
  PlotStyle → {Hue[.7], Hue[.0]}, PlotRange → {-.4, .4}] /. {t0 → 25., ts → 1., tof → 10., f → 1.}
```



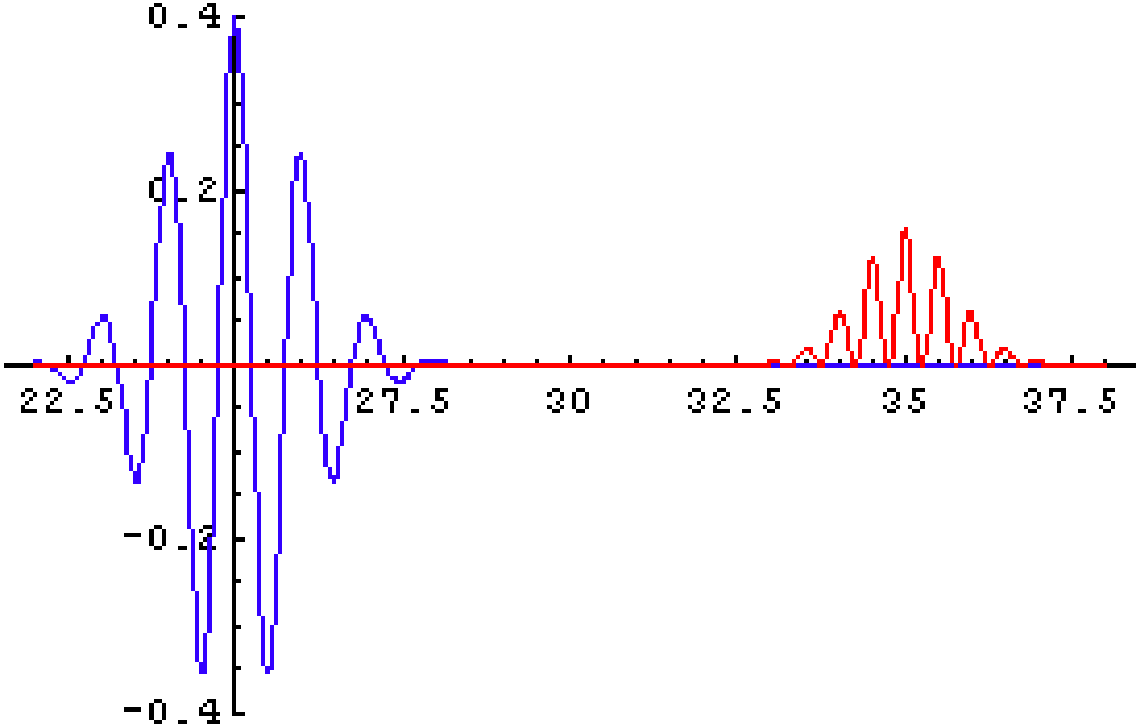
pulse – guess – echo

```
Plot[{gauss[t, t0, ts]         Cos[2 Pi f (t - t0)],
      gauss[t, t0 + tguess, ts] Cos[2 Pi f (t - (t0 + tguess))],
      gauss[t, t0 + tof, ts]    Cos[2 Pi f (t - (t0 + tof))]} ,
     {t, t0 - 3. ts, t0 + tof + 3. ts},
     PlotStyle → {Hue[.7], Hue[.4], Hue[.0]},
     PlotRange → {-.4, .4}] /. {t0 → 25., ts → 1., f → 1, tguess → 8., tof → 10.}
```



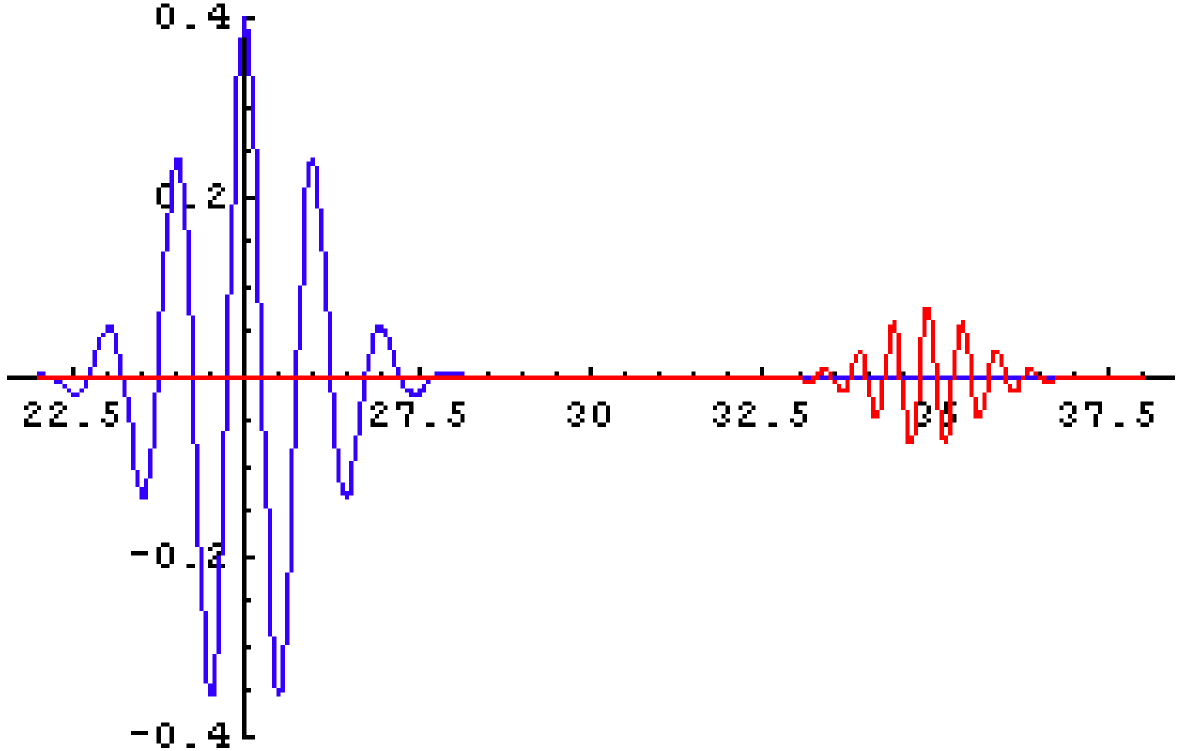
guess * echo when error = 0. period

```
Plot[{gauss[t, t0, ts] Cos[2 Pi f (t - t0)],
    gauss[t, t0 + tguess, ts] Cos[2 Pi f (t - (t0 + tguess))] gauss[t, t0 + tof, ts] Cos[2 Pi f (t - (t0 + tof))]},
   {t, t0 - 3. ts, t0 + tof + 3. ts},
   PlotStyle → {Hue[.7], Hue[.0]},
   PlotRange → {-.4, .4}] /. {t0 → 25., ts → 1., f → 1, tguess → 10., tof → 10.}
```



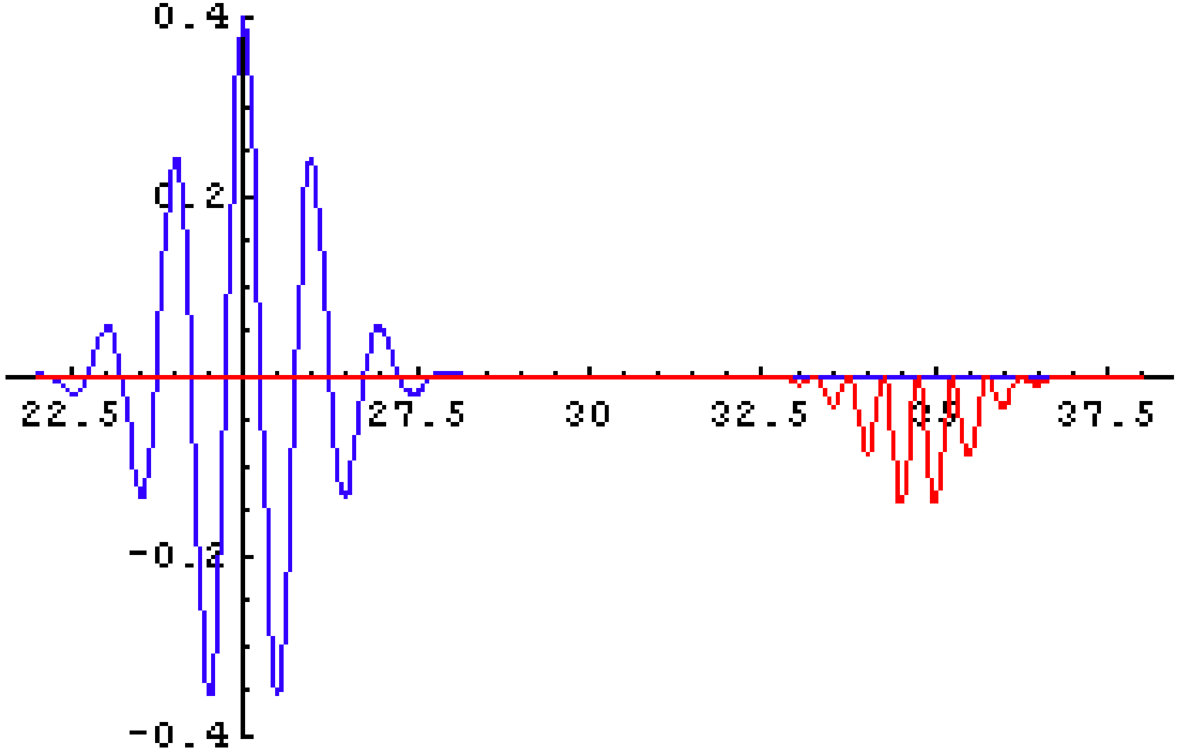
guess * echo when error = .25 period

```
Plot[{gauss[t, t0, ts] Cos[2 Pi f (t - t0)],
    gauss[t, t0 + tguess, ts] Cos[2 Pi f (t - (t0 + tguess))] gauss[t, t0 + tof, ts] Cos[2 Pi f (t - (t0 + tof))]} ,
   {t, t0 - 3. ts, t0 + tof + 3. ts},
   PlotStyle → {Hue[.7], Hue[.0]},
   PlotRange → {-.4, .4}] /. {t0 → 25., ts → 1., f → 1, tguess → 9.75, tof → 10.}
```



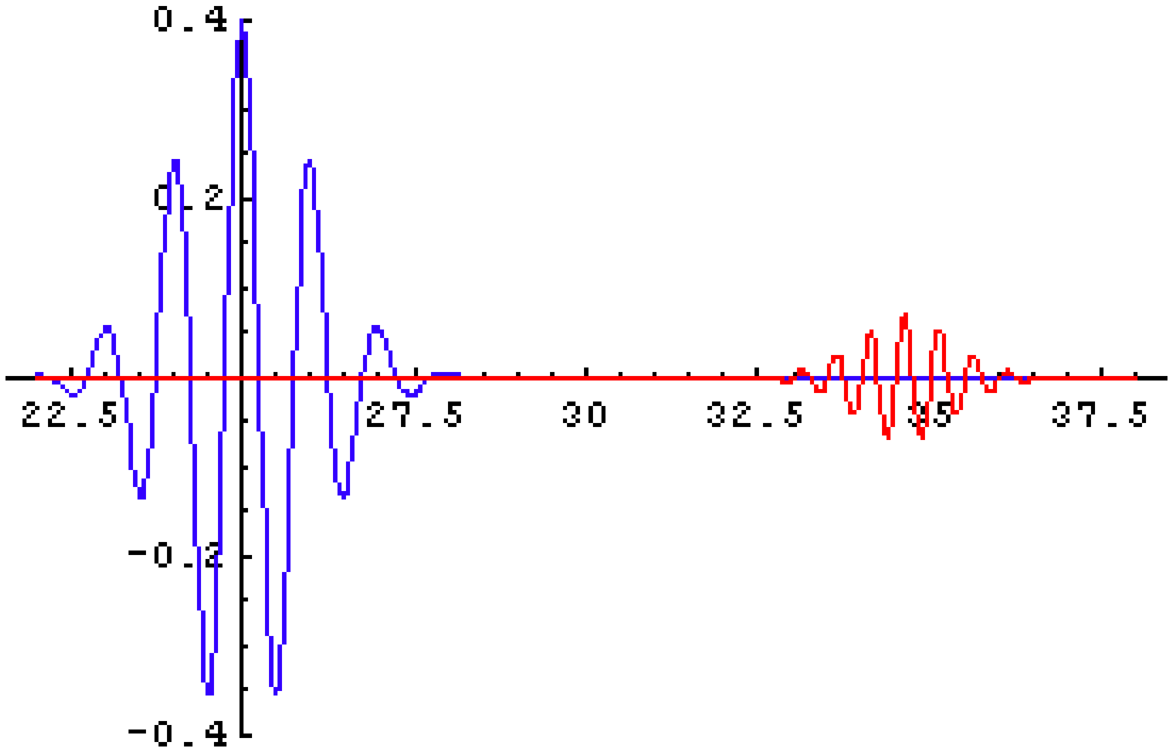
guess * echo when error = .5 period

```
Plot[{gauss[t, t0, ts] Cos[2 Pi f (t - t0)],
     gauss[t, t0 + tguess, ts] Cos[2 Pi f (t - (t0 + tguess))] gauss[t, t0 + tof, ts] Cos[2 Pi f (t - (t0 + tof))]} ,
    {t, t0 - 3. ts, t0 + tof + 3. ts},
    PlotStyle → {Hue[.7], Hue[.0]},
    PlotRange → {-.4, .4}] /. {t0 → 25., ts → 1., f → 1, tguess → 9.5, tof → 10.}
```



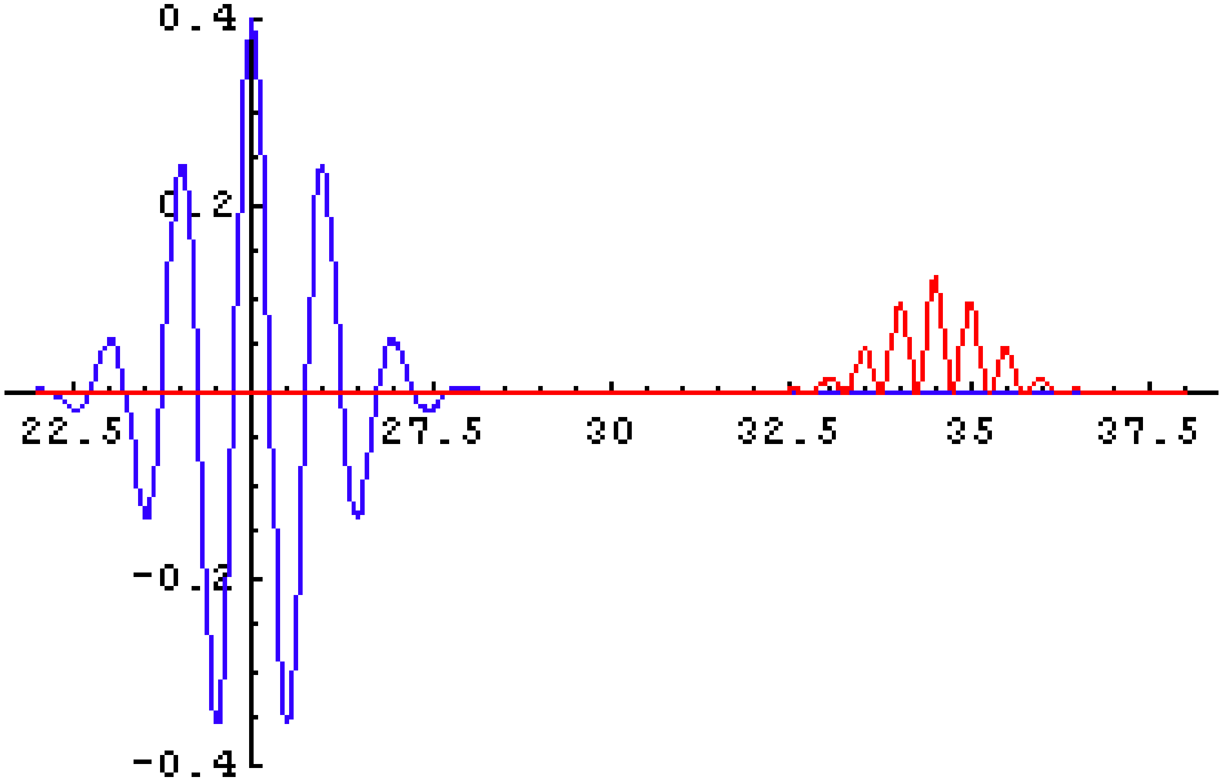
guess * echo when error = .75 period

```
Plot[{gauss[t, t0, ts] Cos[2 Pi f (t - t0)],
     gauss[t, t0 + tguess, ts] Cos[2 Pi f (t - (t0 + tguess))] gauss[t, t0 + tof, ts] Cos[2 Pi f (t - (t0 + tof))]},
    {t, t0 - 3. ts, t0 + tof + 3. ts},
    PlotStyle → {Hue[.7], Hue[.0]},
    PlotRange → {-.4, .4}] /. {t0 → 25., ts → 1., f → 1, tguess → 9.25, tof → 10.}
```



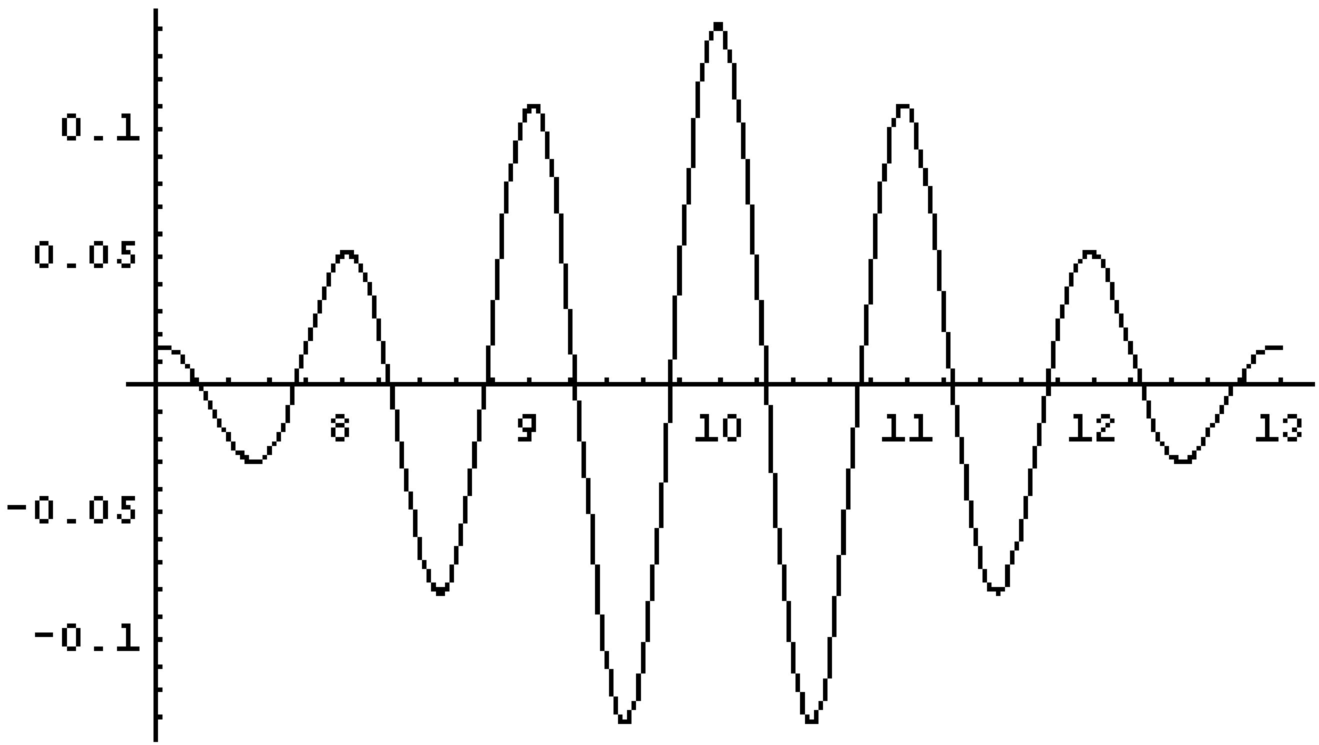
guess * echo when error = 1.0 period

```
Plot[{gauss[t, t0, ts] Cos[2 Pi f (t - t0)],
      gauss[t, t0 + tguess, ts] Cos[2 Pi f (t - (t0 + tguess))] gauss[t, t0 + tof, ts] Cos[2 Pi f (t - (t0 + tof))]},
     {t, t0 - 3. ts, t0 + tof + 3. ts},
     PlotStyle → {Hue[.7], Hue[.0]},
     PlotRange → {-.4, .4}] /. {t0 → 25., ts → 1., f → 1, tguess → 9., tof → 10.}
```



integral of guess * echo over time plotted as function of guess

```
Plot[NIntegrate[gauss[t, t0 + tguess, ts] Cos[2 Pi f (t - (t0 + tguess))] gauss[t, t0 + tof, ts] Cos[2 Pi f (t - (t0 + tof))] ,
    {t, t0 + tguess - 3. ts, t0 + tof + 3. ts}], {tguess, tof - 3. ts, tof + 3. ts}] /. {t0 → 25., ts → 1., f → 1., tof → 10.}
```



exercise

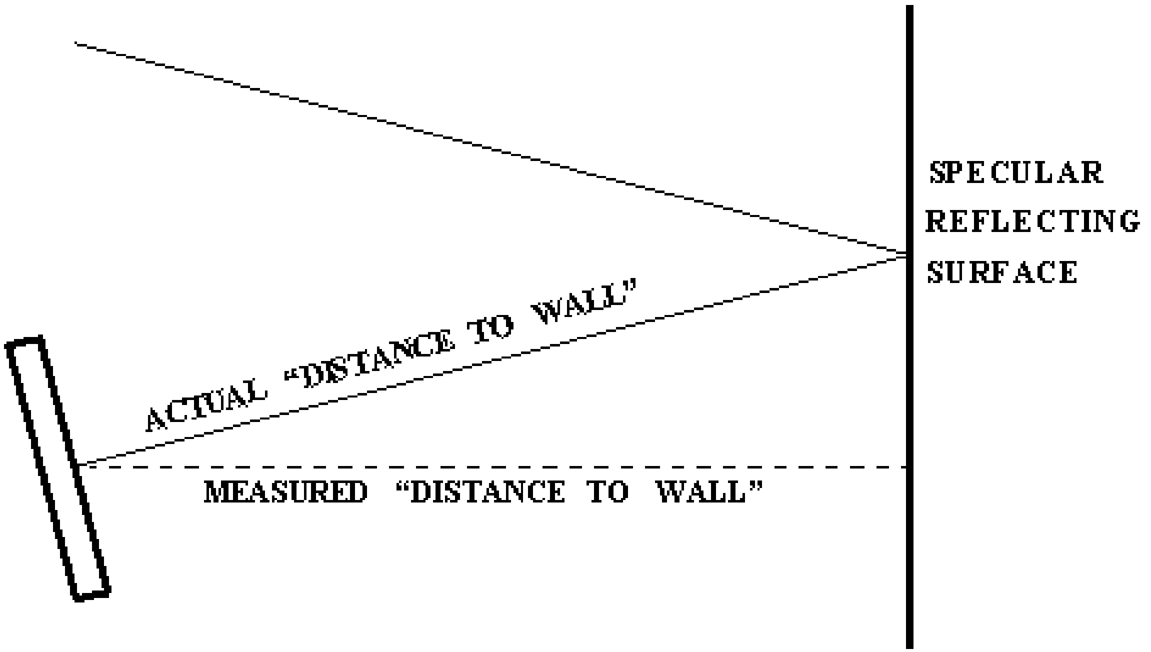
Describe the frequency spectrum of the wave packet used in the previous example.

[hint: In general $\Delta f \, \Delta t \geq 1/(4\pi)$, and for a Gaussian envelope $\geq$ can be replaced by $\approx$. A wave packet that is Gaussian in time has a Gaussian frequency spectrum. Given all that, you need only to estimate its center & width.]

How will *dispersion* and *differential attenuation* affect time-of-flight measured by this method?

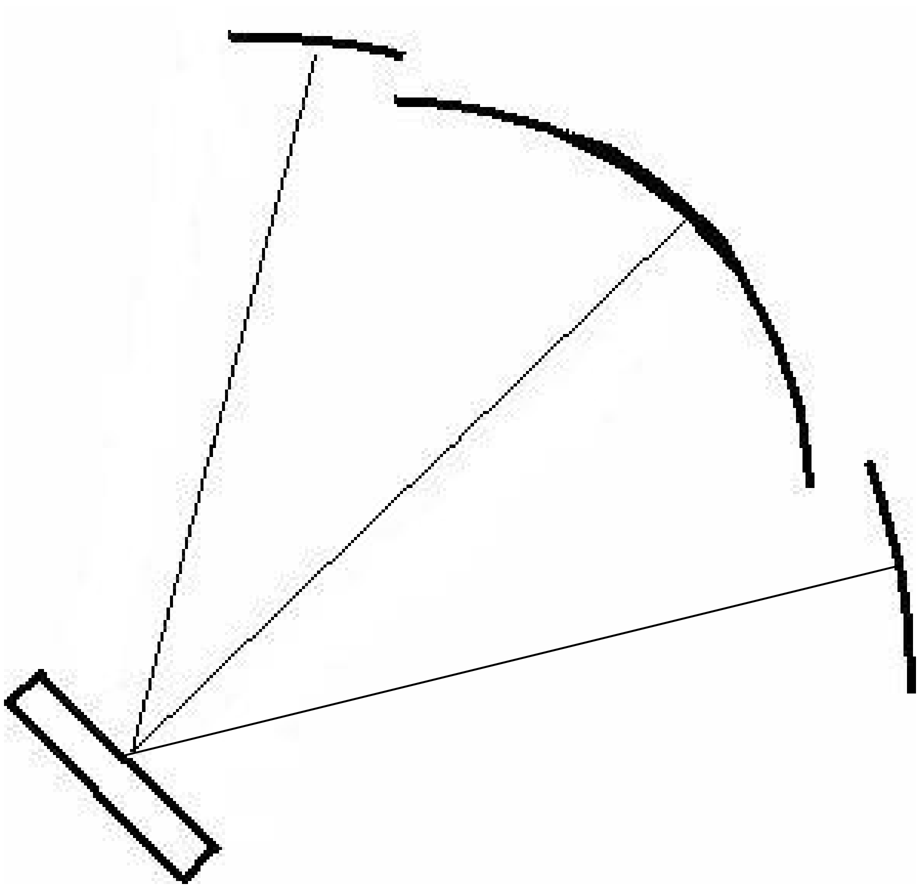
problem: beam width

- specular surfaces are visible – by specular reflection – at “non-specular” angles



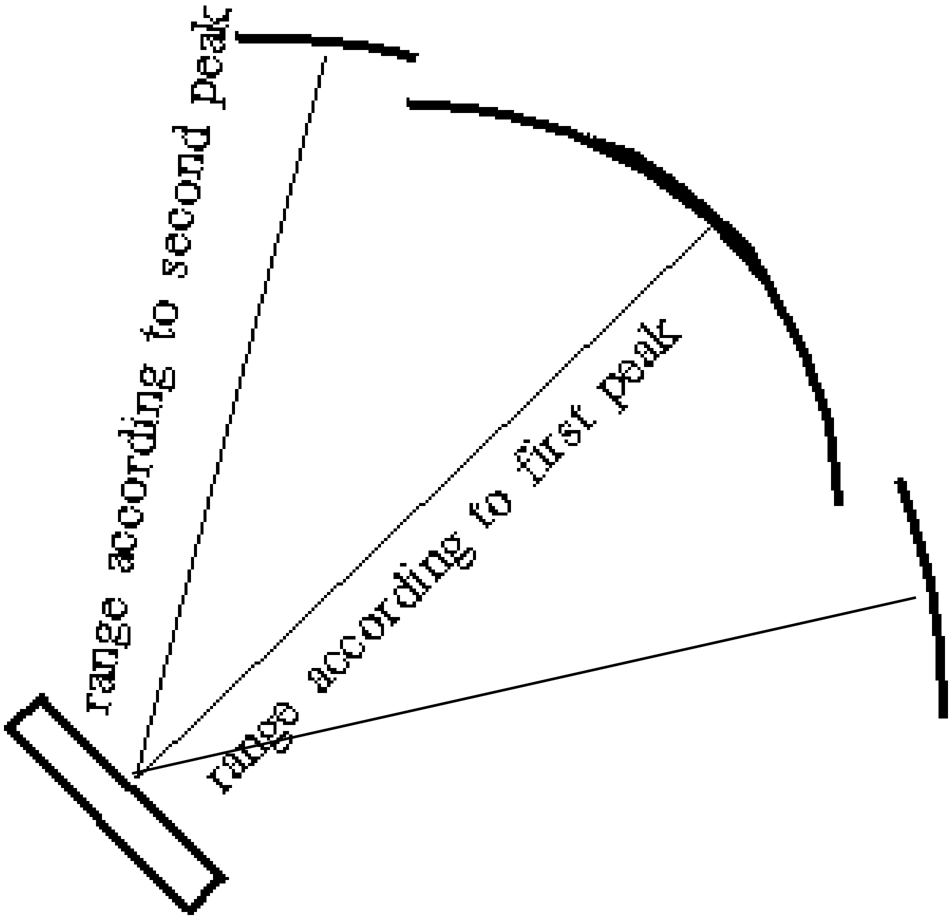
walls appear as arcs in ultrasonic range images (that use co-located transmitter and receiver)

- so walls appear as <u>broken</u> arcs:



(when using threshold detection)

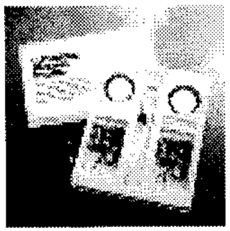
- since as the signal gets weaker (with angle) the apparent time-of-flight gets longer ...



survey of transducers and electronic modules for ultrasonic range sensing

Polaroid (electrostatic) transducers

3-455 - Polaroid Sonar Ranging Kit - $149.00



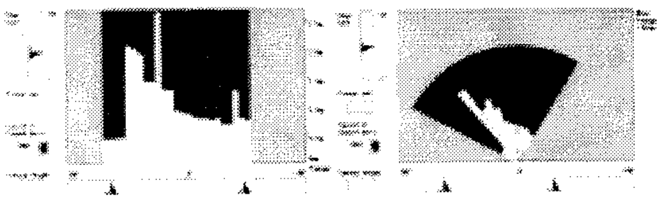
Now you can get the classic Polaroid sonar system in a great experimenters kit. Includes two instrument grade transducers, two drive circuits (fully assembled & tested), plus connectors, tech manual and app notes.

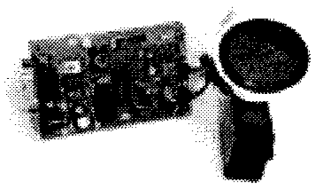
Build them into two robots, or use both on one machine. Easily interfaced to Basic Stamps, BOT-boards, PC parallel port, etc. Detect distances by sonar from 15 cm to 10 meters (6 inches to 33 feet!).

http://www.robotstorehk.com/sensor/sensor.html
http://www.robotstore.com/download/3-740_Sonar_Exp_instr_1.02.pdf

Polaroid-transducer systems

3-705 - Ultrasonic Owl Scanner Kit - $119.00





Give ultrasonic vision to your mobile robot. Fully assembled and tested circuit - no soldering required. Includes Polaroid transducer, housing, servo and cable. Serial interface at 9600 baud (connect to PC, Stamp, BOTBoard, etc.) Measures 0.15 to 2.70 m (0.5 to 10 feet) with 1 cm (1/2 inch) resolution. Simple commands, run in continuous or controlled modes. Includes Windows software (95/98) to display data in both linear and radial modes. Runs on 9 to 12 VDC input. A complete sonar system!

QTY: 0 ORDER VIEW CART

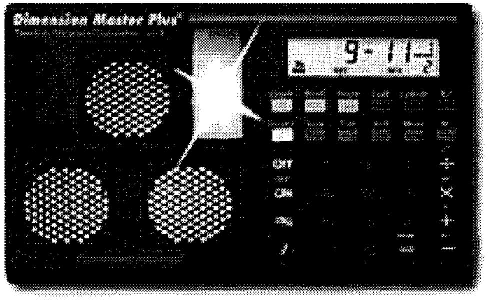
Polaroid-transducer instruments

- What It Does
- Testimonials
- Data Sheet (PDF)
- User Guide (PDF)
- Specifications
- Shopping Polices
- Warranty

- Construction
- Real Estate
- Hobby
- Office & Education
- Film/Video

Dimension Master Plus

Advanced Ultrasonic Tape Measure with Built-in Aiming Light and 3 Polaroid Sensors, for Ultra-Narrow Measuring Beam!



Model #3302 - $129.95

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Click here *for offline ordering.*

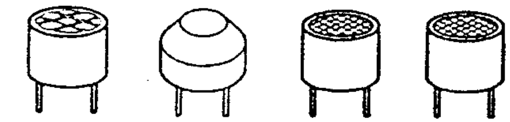
Real Estate Agents/Brokers, Contractors/Builders, Interior Designers, Remodelers & Estimators, Do-It-Yourselfers--Anyone Who Takes Interior or Room Measurements

The advanced Dimension Master Plus is the world's most accurate ultrasonic tape measure, and the only featuring TriSensor Technology, using three Polaroid sensors! The three sensors allow for an ultra-narrow (2-degree) beam for the utmost accuracy. Plus, the Dimension Master Plus features a built-in calculator with dimensional unit conversions.

http://www.calculated.com/UsersGuides/3302mn.pdf

Panasonic (piezoelectric) transmitters and receivers

Panasonic. Ultrasonic Ceramic Sensor/Transducer



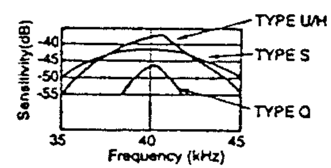
Type H Compact Type* | Type Q Enclosed Type** | Type S Temperature Stable Type** | Type U Standard Type*

* Temperature Range: -20°C to 60°C
** Temperature Range: -40°C to 100°C

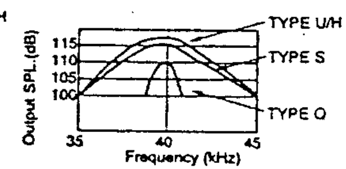
Ultrasonic Ceramic Sensor consisting of a disc/bimorph type piezoelectric ceramic vibrator that is used as a sensor for transmitting and receiving ultrasonics in the air. Since the ultrasonic ceramic sensor has a resonance type vibrator, it is high in sensitivity and has outstanding sound pressure level.

It has wide applications for burglar alarm systems, automatic door openers, flow rate detectors, and remote-control systems in TV, home appliance and toys etc. Sensors are not washable.

Sensitivity



Sound Pressure Level

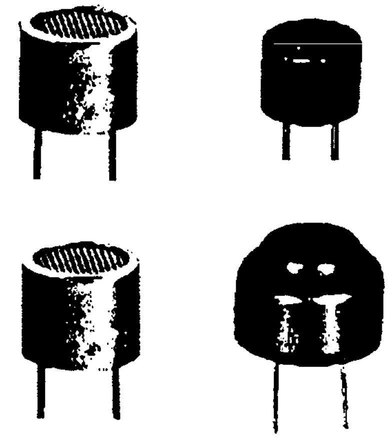


Type	Class	Ctr Freq. 51.0 (KHz)	Sensitivity (dB/V/mbar)	Sensitivity (0dB = 1V/Pa)	Min. Band-Width (KHz)	Sound Pressure Level (dB)	Max. Input Volt. (Vrms)	Dimensions (mm) Physical Size Dia.	Ht.	Leads Length	Leads Space	Digi-Key Part No.	Pricing 1	10	100	500	1,000	Panasonic Part No.
S	Transmitter	41.0	—	—	4.0	110	20	16.0	12.0	10.0	10.0	P9934-ND	6.41	54.21	423.79	1493.50	2816.00	EFR-OSB40K2
S	Receiver	40.0	-67	-47	4.0	—	—	16.0	12.0	10.0	10.0	P9935-ND	6.39	54.10	422.98	1490.50	2811.00	EFR-RSB40K2
Q	Transmitter	39.8	—	—	2.0	105	20	18.0	12.0	12.5	7.5	P9938-ND	25.74	217.80	1702.80	6000.00	11314.00	EFR-OQB40K4
Q	Receiver	39.5	-75	-55	2.0	—	—	18.0	12.0	12.5	7.5	P9939-ND	22.62	191.40	1496.40	5272.50	9943.00	EFR-RQB40K4
U	Receiver	40.0	-65	-45	4.0	—	—	16.0	12.0	10.0	10.0	P9888-ND ***NEW!***	5.13	43.40	339.29	1195.51	2254.40	EFR-RUB40K5
U	Transmitter	40.0	—	—	4.0	112	20	16.0	12.0	10.0	10.0	P9889-ND ***NEW!***	5.13	43.40	339.29	1195.51	2254.40	EFR-TUB40K5
H	Receiver	40.0	-67	-47	4.0	—	—	12.6	9.5	6.0	8.0	P9890-ND ***NEW!***	7.87	66.56	520.37	1833.57	3457.60	EFR-RHB40K5
H	Transmitter	40.0	—	—	4.0	110	20	12.6	9.5	6.0	8.0	P9891-ND ***NEW!***	7.87	66.56	520.37	1833.57	3457.60	EFR-THB40K5
Q	Receiver	40.0	-75	-55	1.0	—	—	18.0	12.0	12.5	7.5	P9892-ND ***NEW!***	29.79	252.10	1970.95	6944.84	13095.99	EFR-RQB40K5
Q	Transmitter	40.0	—	—	1.0	105	20	18.0	12.0	12.5	7.5	P9893-ND ***NEW!***	29.79	252.10	1970.95	6944.84	13095.99	EFR-TQB40K5
S	Receiver	40.0	-70	-50	4.0	—	—	16.0	12.0	10.0	10.0	P9894-ND ***NEW!***	6.45	54.61	426.94	1504.36	2836.80	EFR-RSB40K5
S	Transmitter	40.0	—	—	4.0	105	20	16.0	12.0	10.0	10.0	P9895-ND ***NEW!***	6.45	54.61	426.94	1504.36	2836.80	EFR-TSB40K5

超音波セラミックセンサ

Ultrasonic Ceramic Sensors (Ultrasonic Ceramic Transducers)

Type U/H/S/Q



■特長

- ●高音圧レベル（110 dB以上）
- ●独自の新構造により高感度（−45 dB以上）
- ●小形設計
- ●すぐれた温度・耐湿特性
- ●広帯域幅なので多ファンクションのリモコンにも使用可能

■用途

- ●テレビ・ステレオ・ルームクーラー・扇風機・ガレージのドア開閉等のワイヤレスリモコン装置。
- ●盗難防止器・パーキングメータ・自動ドア・流量検出器等の近接スイッチ。

Features

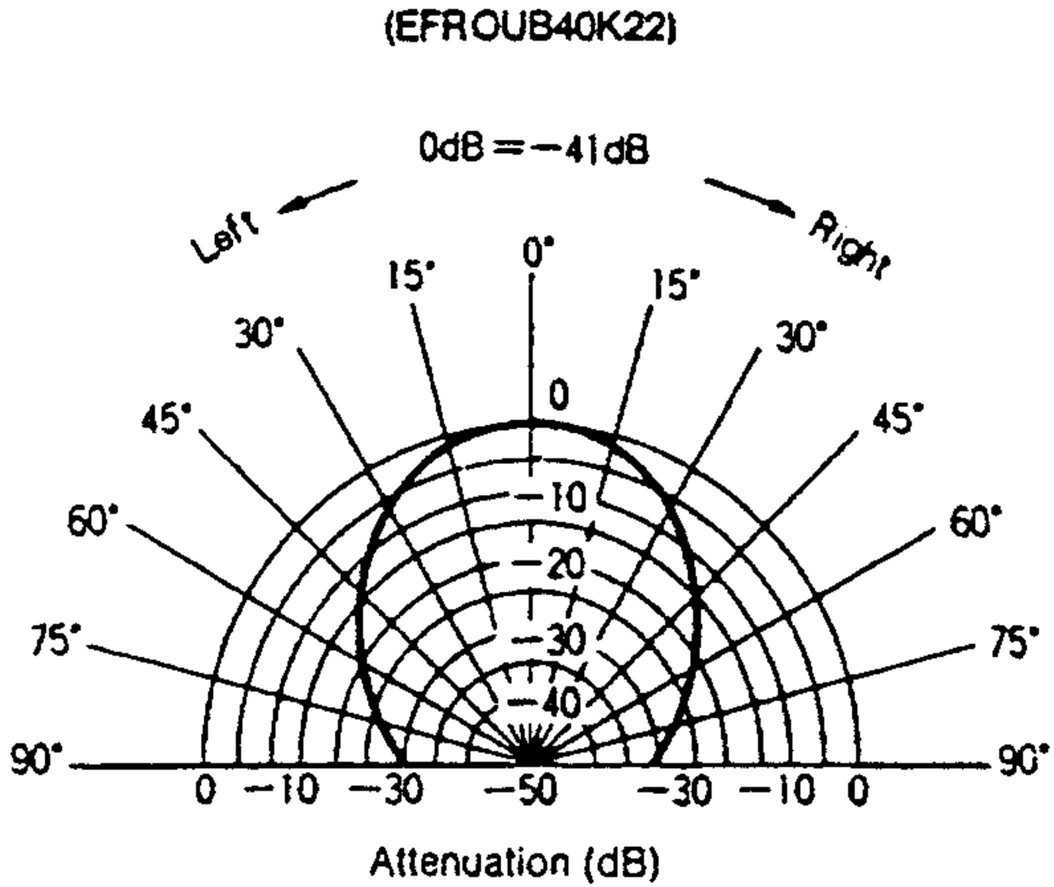
- ●High output S.P.L.: 110 dB min.
- ●High sensitivity: −45 dB min.
- ●Excellent temperature and humidity durability
- ●Small in size
- ●Applicable to multi-function remote control system because of its wide bandwidth

Applications

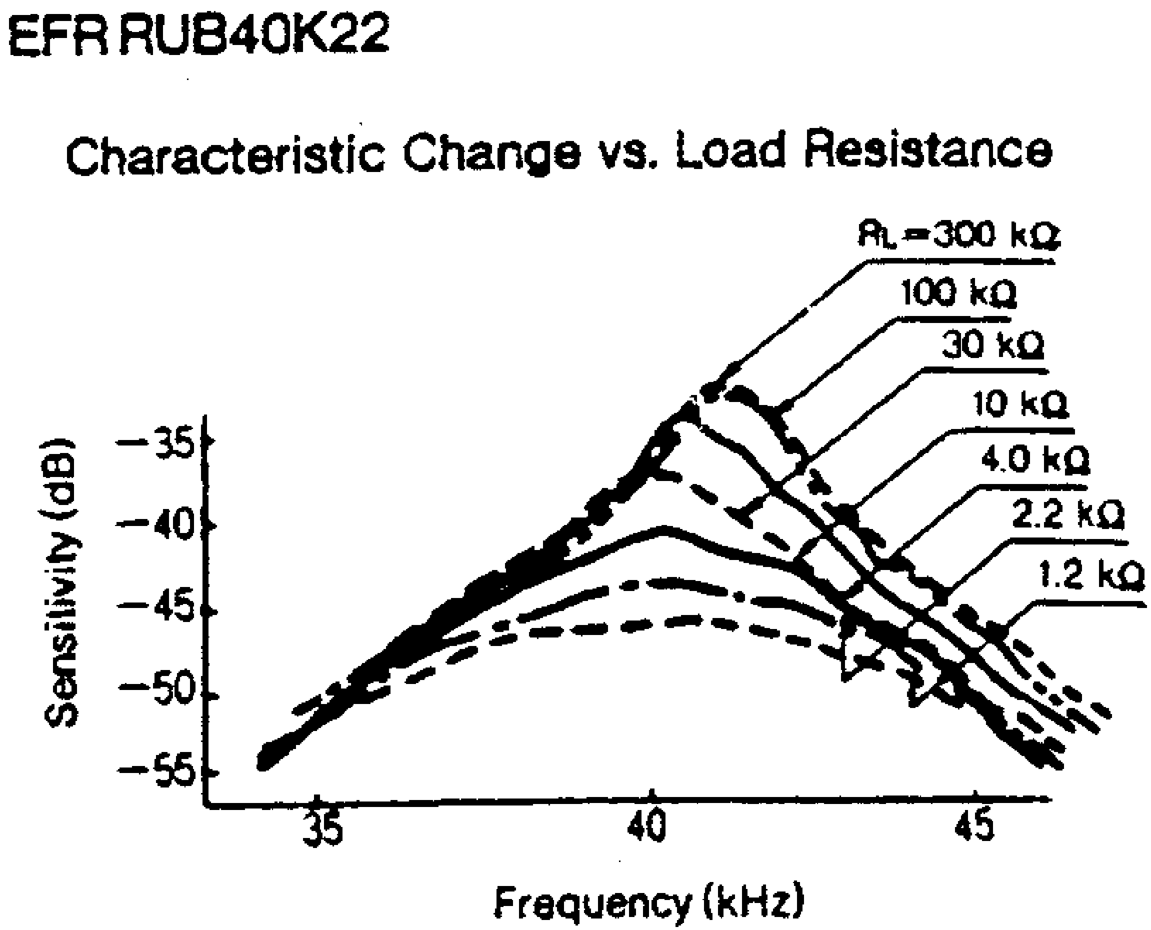
Ultrasonic wave transmitter and receiver for:

- ●Remote control equipment for such as TV, air conditioner and garage door opener etc.
- ●Proximity switch for burglar alarm system,parking meter and automatic door opener etc.

beam “width” (angular distribution)

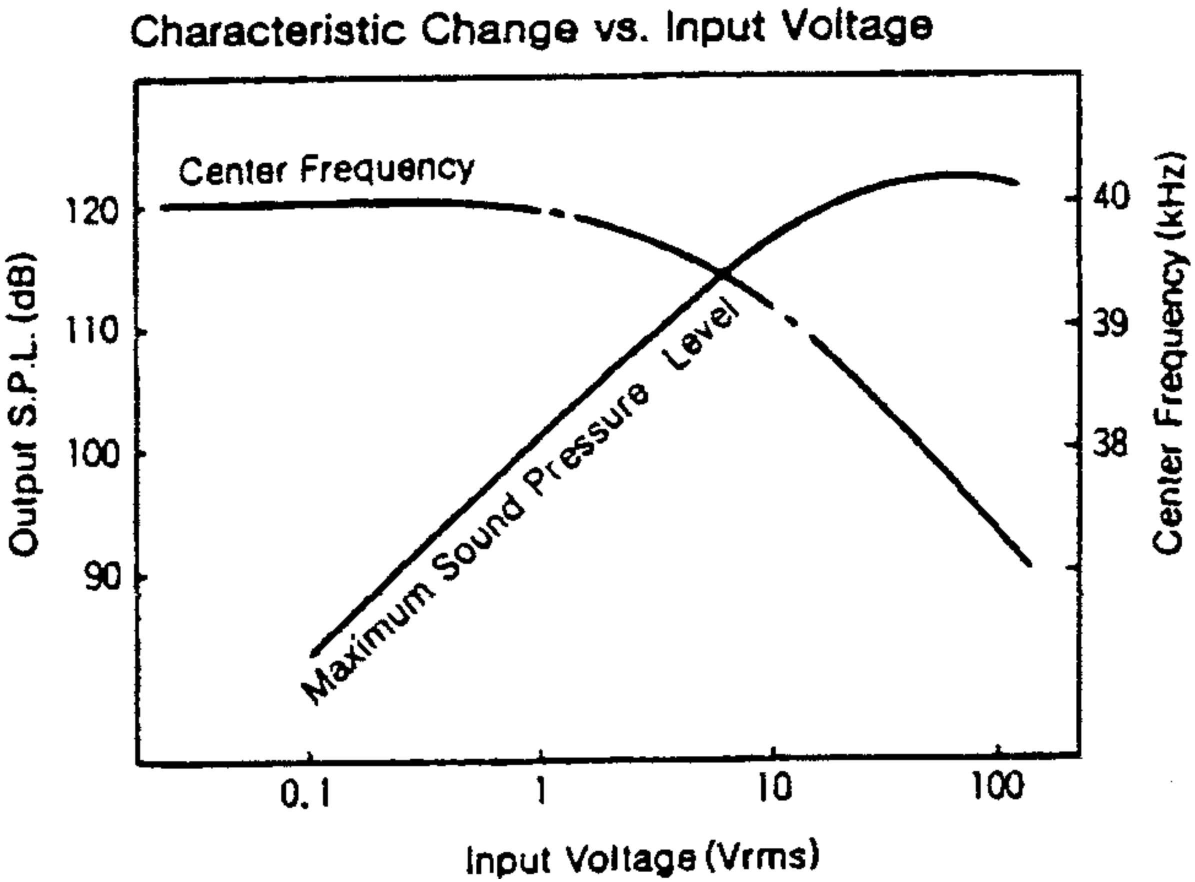


sensitivity vs. frequency & load



frequency & output vs. drive

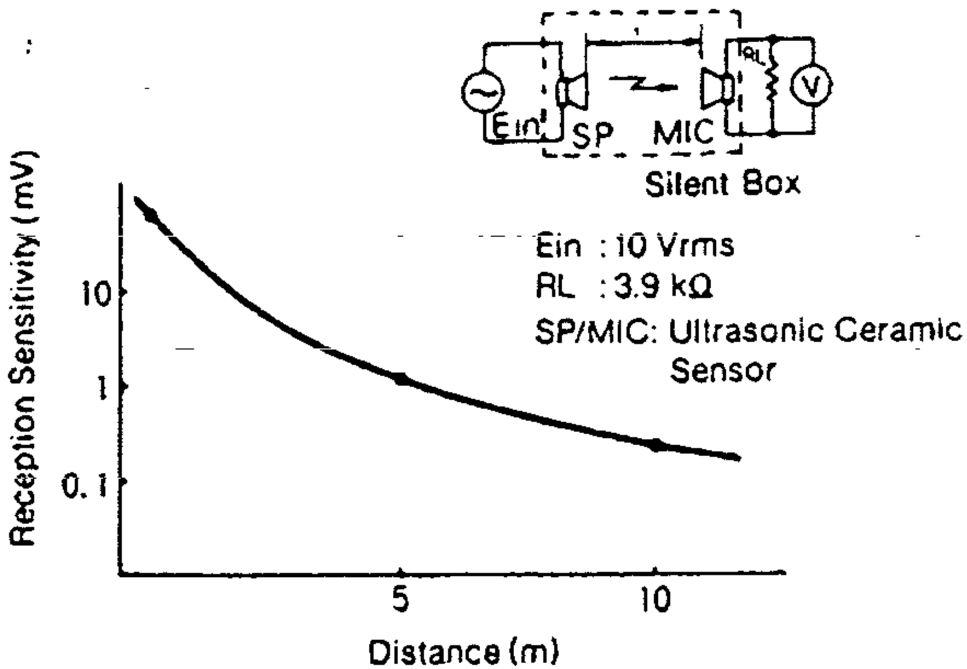
EFROUB40K22



received signal vs. distance

EFRRUB40K22
EFROUB40K22

Distance vs. Reception Sensitivity

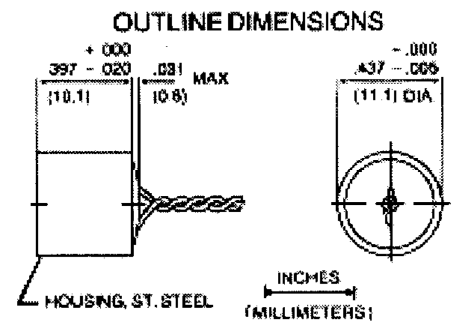


Massa 40 kHz & 75 kHz Models

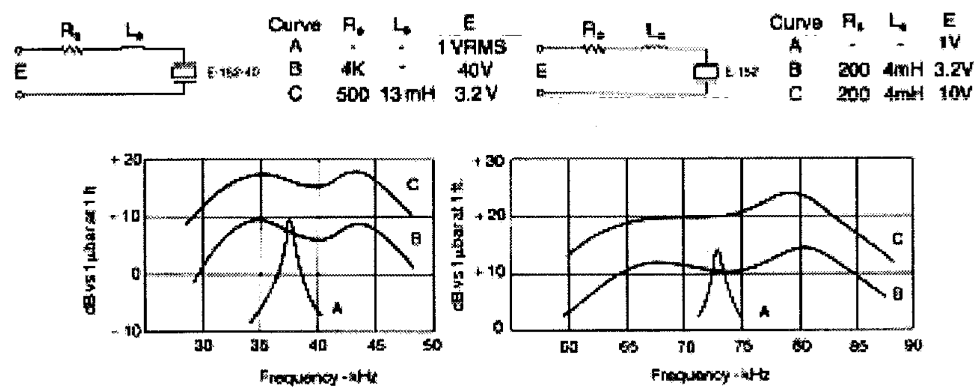
Specifications

	E-152/40	E-152/75
Frequency at Receiving Sensitivity	40 kHz +/- 2kHz	75 kHz +/-2 kHz
Bandwidth		
Tuned	14 kHz	20 kHz
Untuned	1 kHz	1 kHz
Transmitting Sensitivity (dB vs. 1 µbar per volt at 1 ft. untuned	+10	+10
Receiving Sensitivity (dB vs. 1 volt/µbar	-57	-62

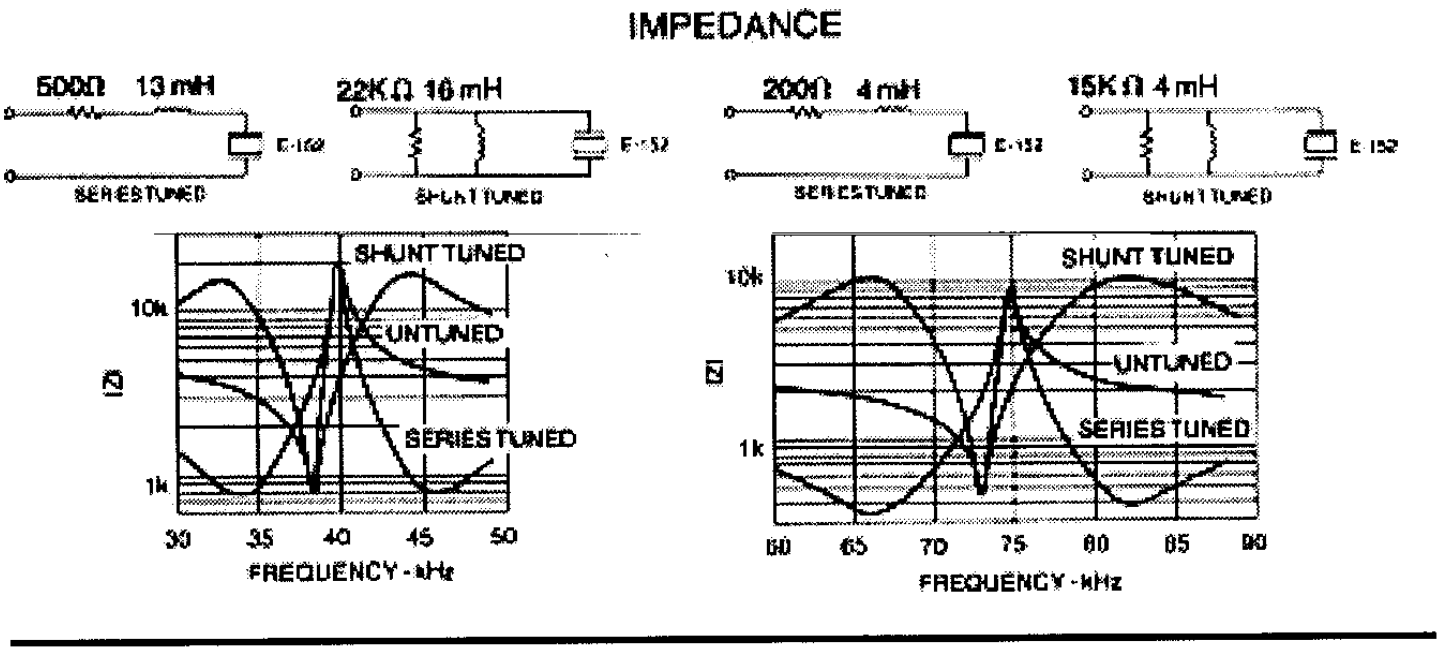
OUTLINE DIMENSIONS

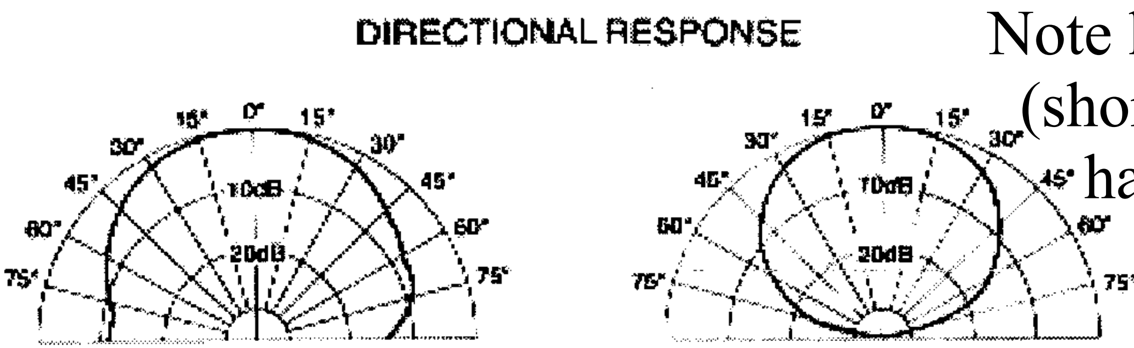


TRANSMITTING RESPONSE



impedance & angular distribution





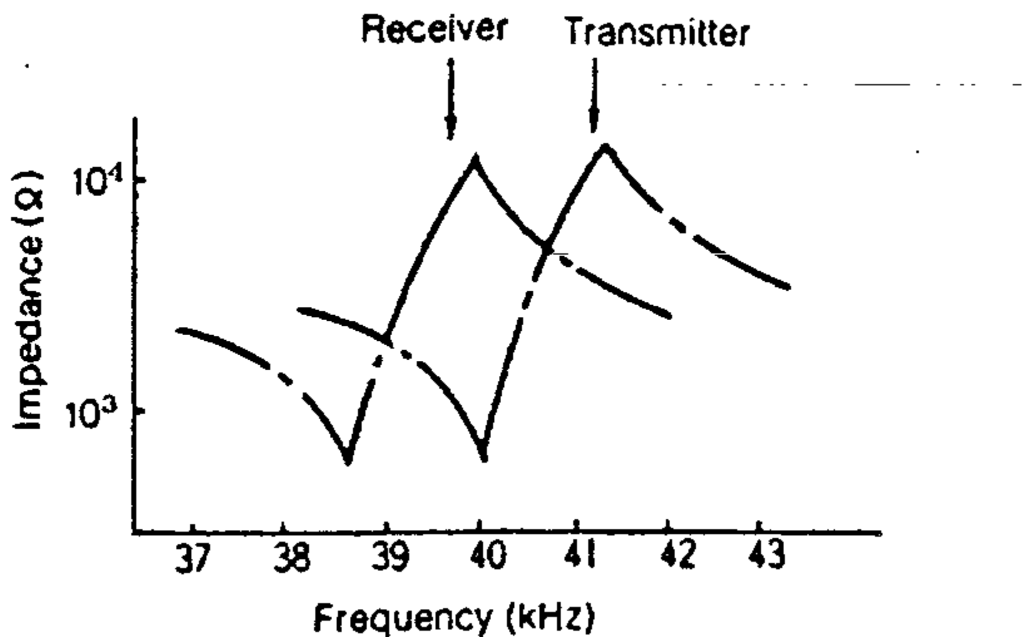
Note higher frequency (shorter wavelength) has narrower beam

the “strange” resonance characteristics of piezo-electric transducers

resonance characteristics

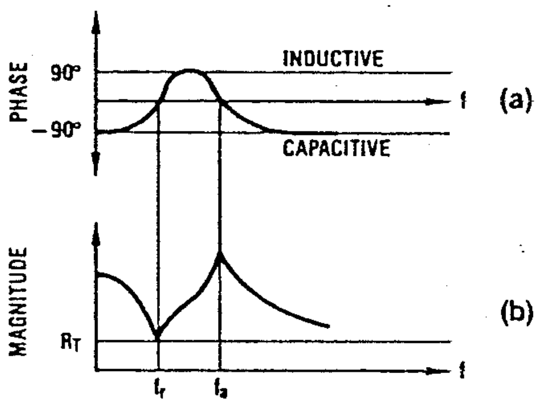
EFR RUB40K22
EFR OUB40K22

Frequency Characteristics of Resonator



impedance vs. frequency

The most common transducer used with the LM1812 is the piezo-ceramic type which is electrically similar to a quartz crystal. Piezo-ceramic transducers are resistive at only two frequencies, termed the resonant and antiresonant (f_r, f_a) frequencies. Elsewhere these transducers exhibit some reactance as shown in *Figure 3.*



TL/H/7892-3

FIGURE 3. Phase and Magnitude of Transducer Impedance

For transmitting (to maximize electrical to mechanical efficiency), the transducer should be operated at its resonant frequency. For receiving (to maximize mechanical to electrical efficiency), optimum operation is at antiresonance. In two-transducer systems the resonant frequency of the transmit transducer is matched to the antiresonant frequency of the receiver.

The LM1812 is primarily used with a single transducer performing both transmit and receive functions. In this mode, maximum echo sensitivity will occur at a frequency close to resonance.

Transducer ringing is a troublesome phenomenon of single transducer systems. After a transducer has been electrically driven in the transmit mode, some time is required for the mechanical vibrations to stop. Depending on the amount of damping, this ringing may last from 10 to 1000 cycles. This mechanical ring produces an electrical signal strong enough (>200 μVp-p) to hold the detector ON, thus masking any echo signals occurring during this time.

A solution to this ring problem is to vary the receiver gain from a minimum, just after transmit, to a maximum, when the ring signal has dropped below the full-gain detection threshold. Since near-range echo signals are much stronger than ring signals, close echos will still be detected in spite of the reduced gain.

The gain is varied by attenuating the signal between pins 2 and 3 of the LM1812. *Figure 4* shows such an arrangement. An externally generated 12V pulse (*Figure 17*) keys the transmitter and activates the attenuator. This pulse charges C to a voltage set by P8, turning the FET OFF. C slowly discharges through R, decreasing the gate voltage, which in turn decreases the attenuation of the signal passing from pin 3 to pin 2. R and C are selected so that the FET is not

sonar electronics modules

time-dependent amplification

- receiver amplifier gain is typically “ramped” approximately linearly with time after acoustic pulse emission
- this helps suppress direct coupling (i.e., not via echo) between transmitted pulse and electronic detection circuit
- but primarily it is used to compensate signal strength fall off with distance
- but you can’t do it forever … eventually you’ll just be amplifying noise

circuit layout issues to achieve isolation of transmit and receive

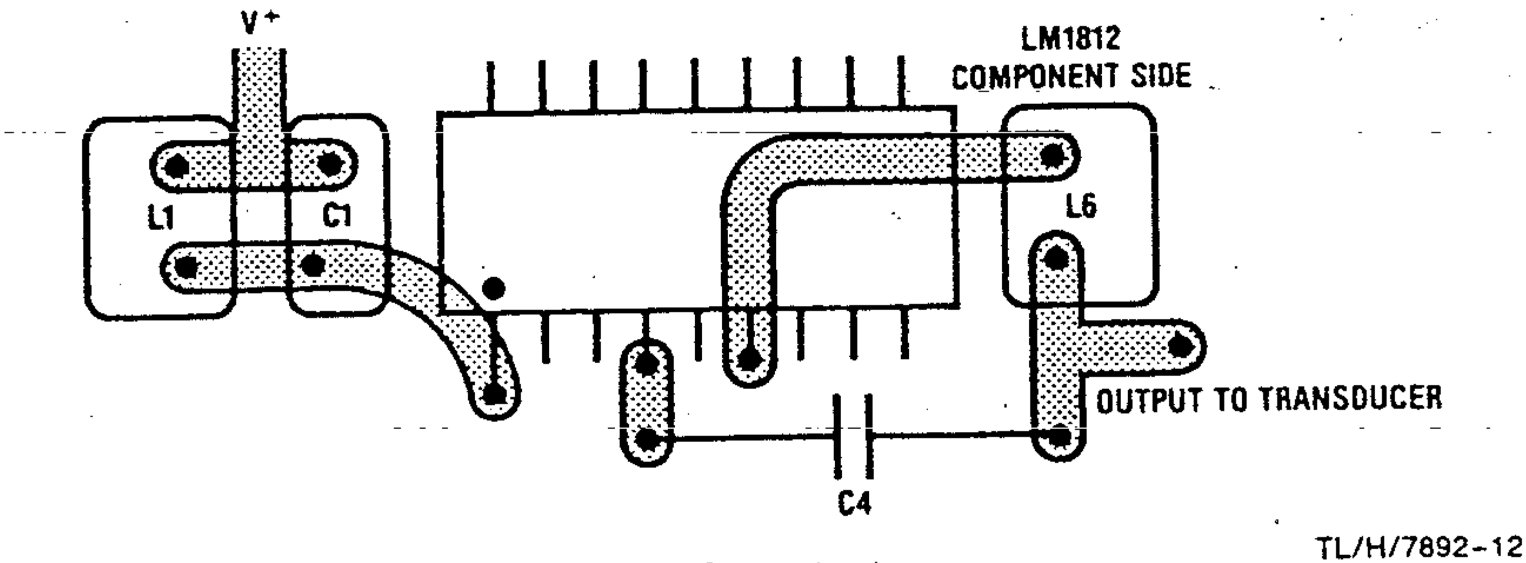


FIGURE 11. Component Side of Layout Showing Isolation of Receiver Input and Output

IC for sonar applications

LM1812

National Semiconductor

LM1812 Ultrasonic Transceiver

General Description

The LM1812 is a general purpose ultrasonic transceiver designed for use in a variety of ranging, sensing, and communications applications. The chip contains a pulse-modulated class C transmitter, a high gain receiver, a pulse modulation detector, and noise rejection circuitry.

A single LC network defines the operating frequency for both the transmitter and receiver. The class C transmitter output drives up to 1A (12W) peak at frequencies up to 325 kHz. The externally programmed receiver gain provides a detection sensitivity of 200 μVp-p. Detection circuitry included on-chip is capable of rejecting impulse noise with external programming. The detector output sinks up to 1A.

Applications include sonar systems, non-contact ranging, and acoustical data links, in both liquid and gas ambients.

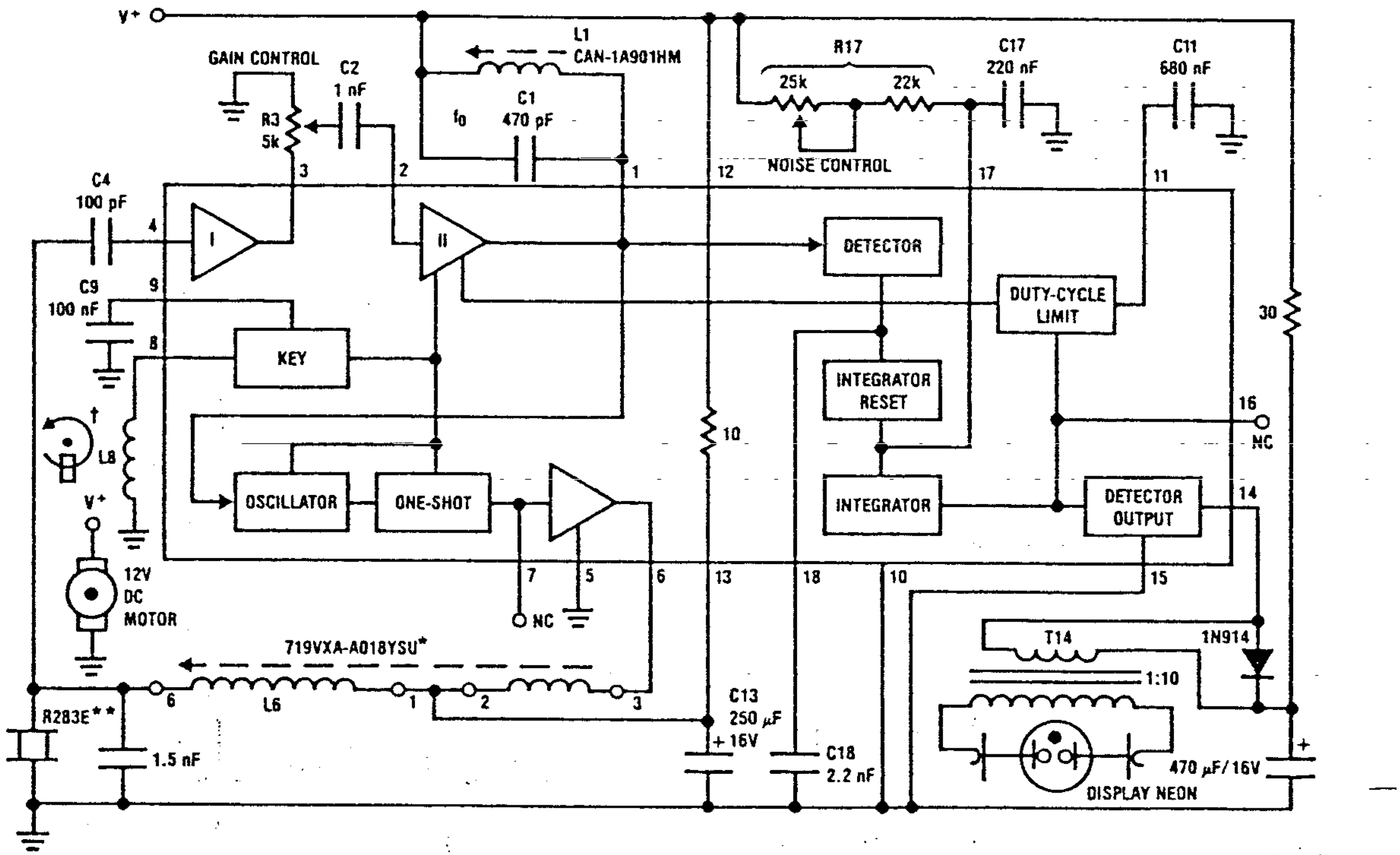
Features

- One or two-transducer operation
- Transducers interchangeable without realignment
- No external transistors
- Impulse noise rejection
- No heat sinking
- Protection circuitry included
- Detector output drives 1A peak load
- Ranges in excess of 100 feet in water, 20 feet in air
- 12W peak transmit power

Applications

- Liquid level measurement
- Sonar
- Surface profiling
- Data links
- Hydroacoustic communications
- Non-contact sensing
- Industrial process control

circuit functional details



Order Number LM1812N
See NS Package Number N18A

TI TL851/2 hybrid analog-digital

- Designed for Use With the TL851 in Sonar Ranging Modules Like the SN28827
- Digitally Controlled Variable-Gain Variable-Bandwidth Amplifier
- Operational Frequency Range of 20 kHz to 90 kHz
- TTL-Compatible
- Operates From Power Sources of 4.5 V to 6.8 V
- Interfaces to Electrostatic or Piezoelectric Transducers
- Overall Gain Adjustable With One External Resistor

- often used with Polaroid (electrostatic) transducers as alternative to the Polaroid-supplied electronics

some issues in quantitative ultrasonic imaging

e.g., in medical imaging …

- speed of sound in “flesh and blood” is:
  - not known
  - not constant (even in one individual subject)
  - not amenable to measurement using “manufactured artifacts”
- so if precisely scaled range is needed, an “in situ” calibration method is required

- “average” or “typical” values are fine:
  - for qualitative visualization, pathology / diagnosis, etc
  - but probably not for, e.g., custom design of wheelchair cushions
  - and certainly not for, e.g., planning a micro-surgical path

problem

- image guided surgery literature seeks:
  - navigational accuracy ~ 1 mm
  - endpoint precision ~ 0.1 mm

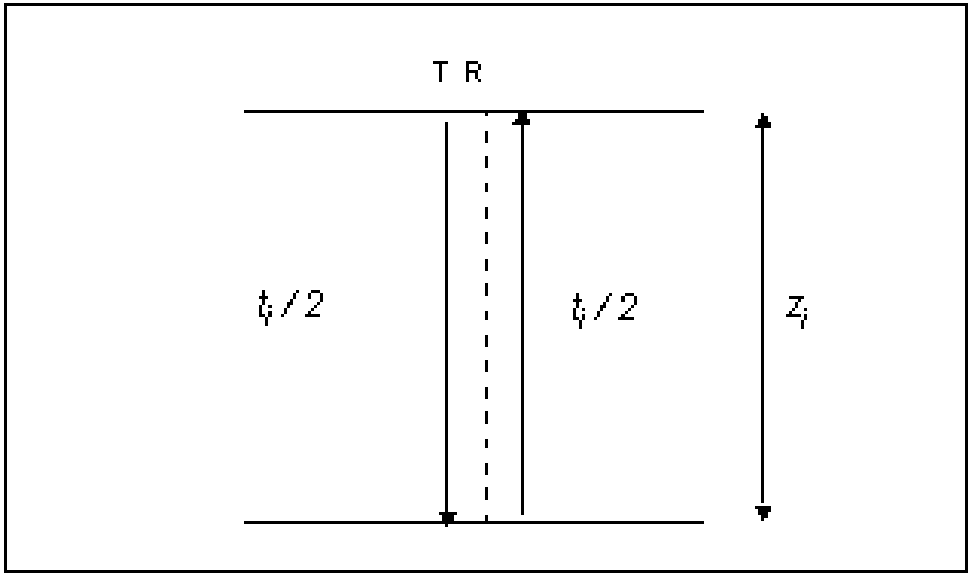
- ignorance of precise acoustic properties of skin, fat, muscle, etc, layers makes these specifications problematic

approach

- identify elementary cases
- invent in situ calibration protocols for them:
  - multiple parallel homogeneous layers
  - speed of sound gradient in a single layer
  - a tapered layer
- assume
  - any real case is a (separable) combination of the elementary cases
  - mechanically accurate scanning capability

basic ToF technique

- a single-sided ultrasonic thickness measurement method
  - presumes speed of sound c_i is known

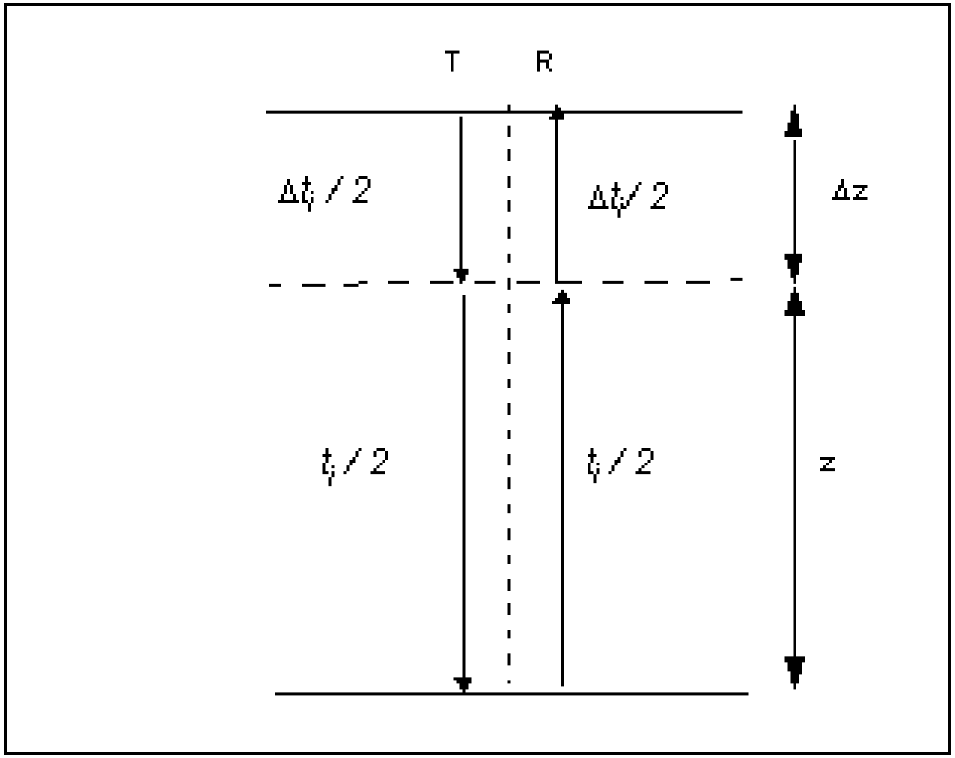


c_i known

measure: t_i

calculate: $z_i = c_i\, t_i / 2$

- and a differential method
  - presumes speed of sound c_i does not change with thickness



c_i unknown

measure: t_i, Δt_i, Δz_i

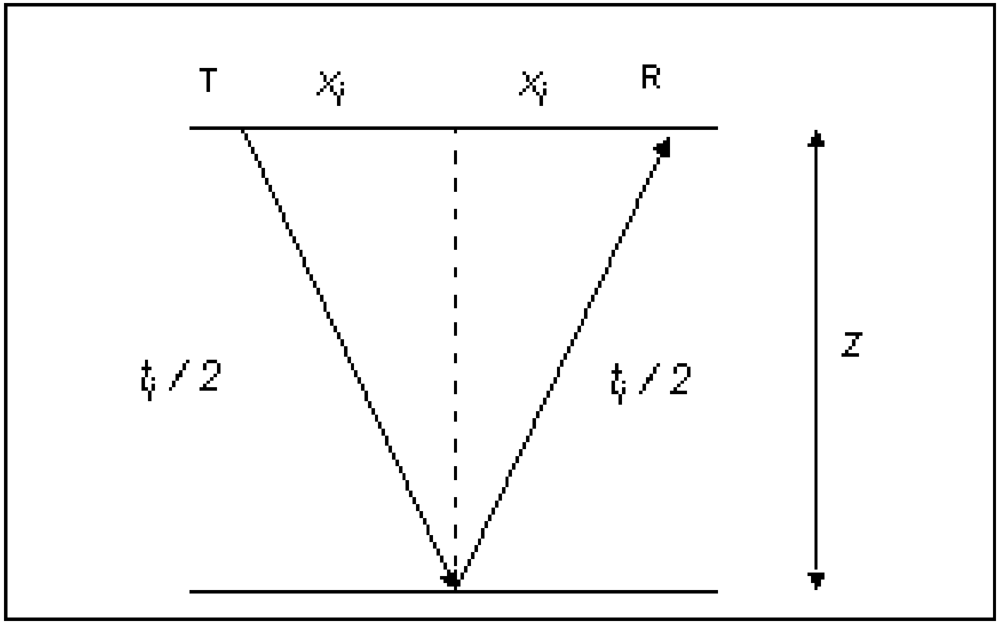
calculate: c_i and z_i

$c_i = 2\ \Delta z_i / \Delta t_i$

$z_i = c_i\ t_i/2$

one homogeneous layer

- two (or more) oblique paths
  - overcomes the presumptions of the normal path methods
  - however, possible confusion from diffuse reflection!
  - if $i>2$ a least-squares solution will optimize accuracy



c unknown

measure: $\{x_1, t_i\}$

calculate: c and z

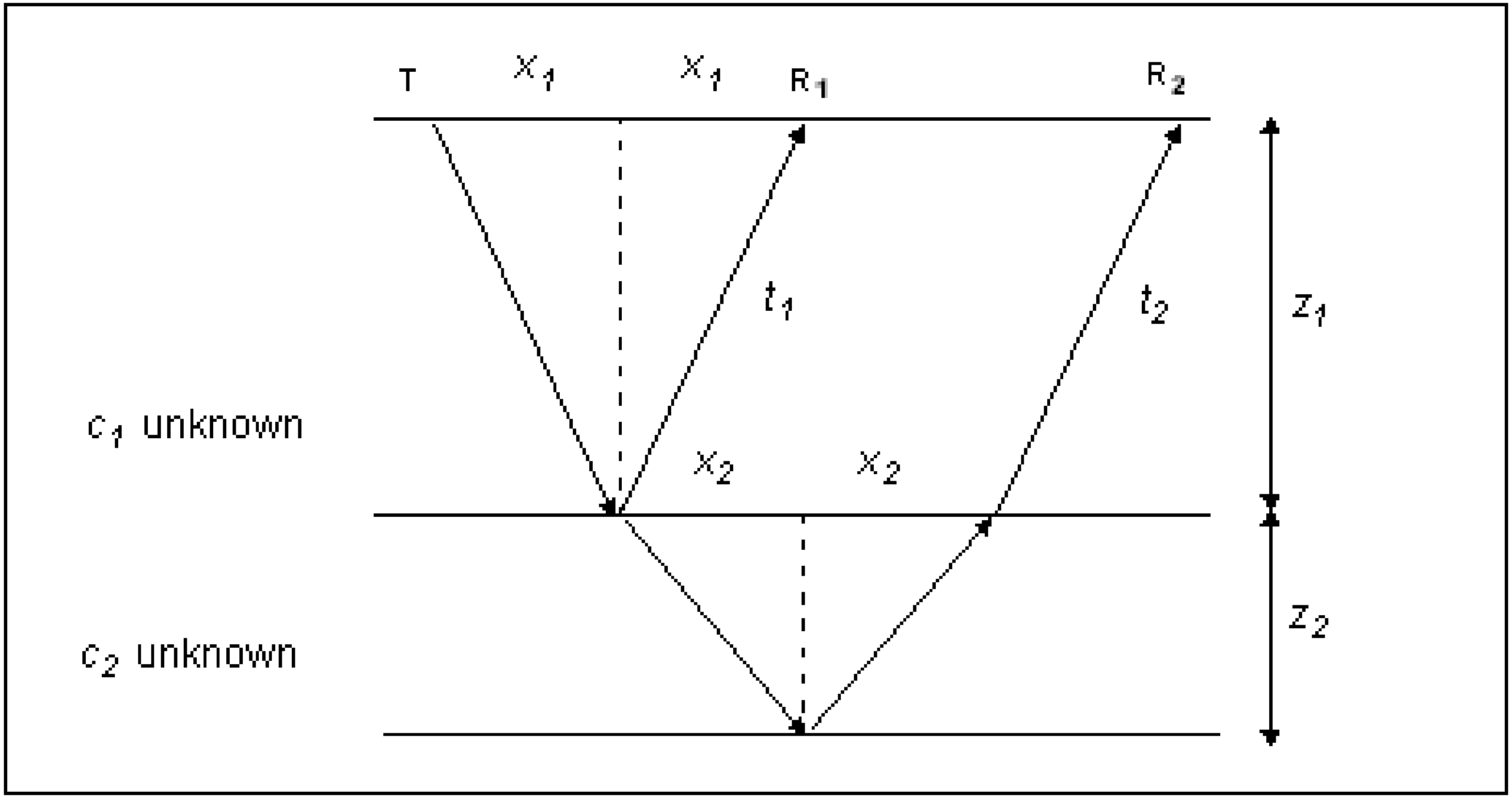
$$c^2 \cdot \frac{t_i^2}{4} = z^2 + x_i^2$$

$$c = \frac{2\sqrt{x_i^2 + z^2}}{t_i}$$

$$z = \sqrt{\frac{x_2^2 \cdot t_1^2 - x_1^2 \cdot t_2^2}{t_2^2 - t_1^2}}$$

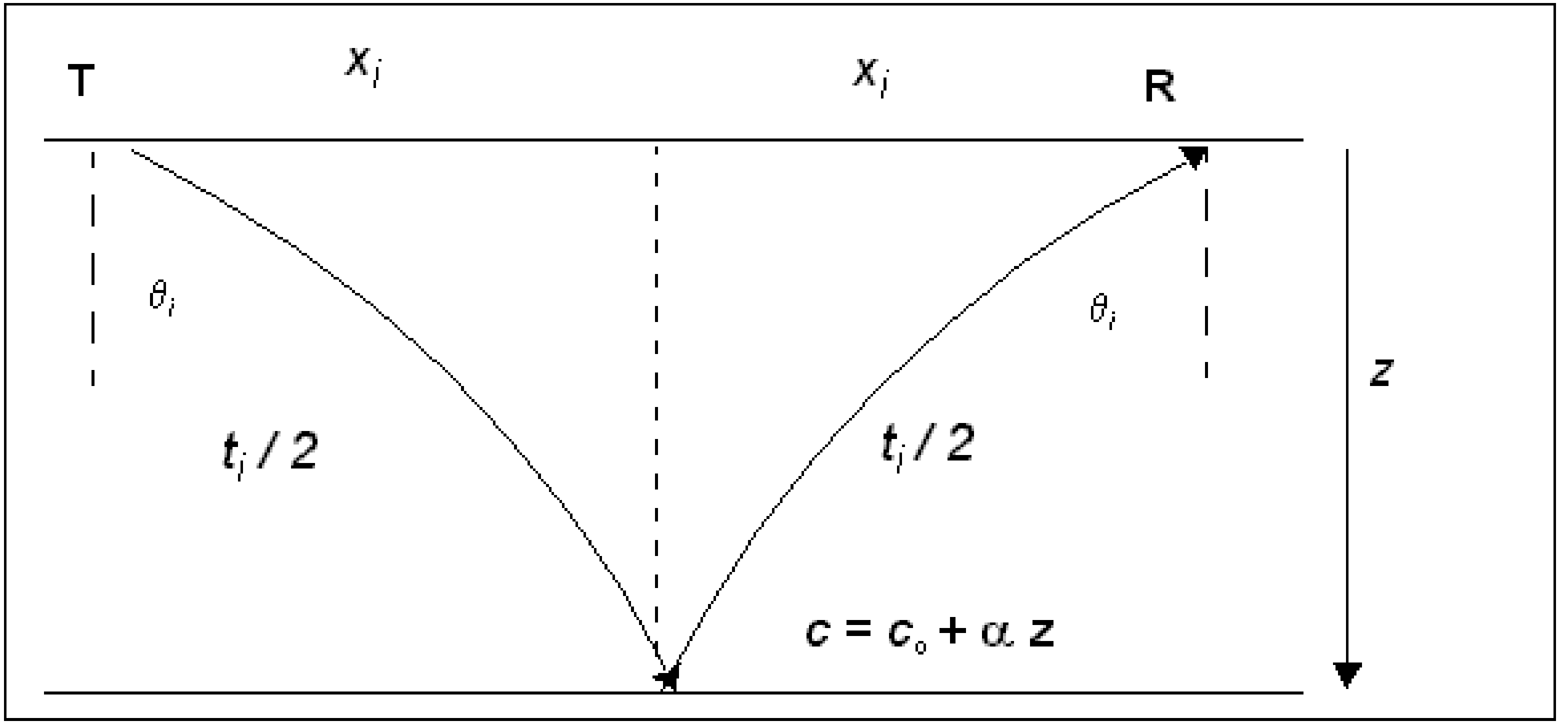
several parallel homogeneous layers

- select two values of x_1; measure corresponding two values of x_2
  - mainstay of geoacoustics, e.g., oil prospecting in complex rock strata
  - need to assume the paths are distinguishable by, e.g., signal amplitude


T
x1
x1
R1
R2
t1
t2
z1
c1 unknown
x2
x2
z2
c2 unknown

parallel layers with velocity gradient

- $\sin\theta / c = k$ holds even if *c* is a function of position
  - acoustic trajectory is then curved)
- continuous *c* causes refraction but not reflection
- if *c* is a linear function of position (depth) then the curved path is a circular arc
- this result is a mainstay of underwater acoustics, where temperature and salinity gradients lead to speed-of-sound gradients
- three T/R separations are enough to measure c_0, z, and the launch angles $\{\theta_1, \theta_2, \theta_3\}$ corresponding to the chosen $\{x_1, x_2, x_3\}$



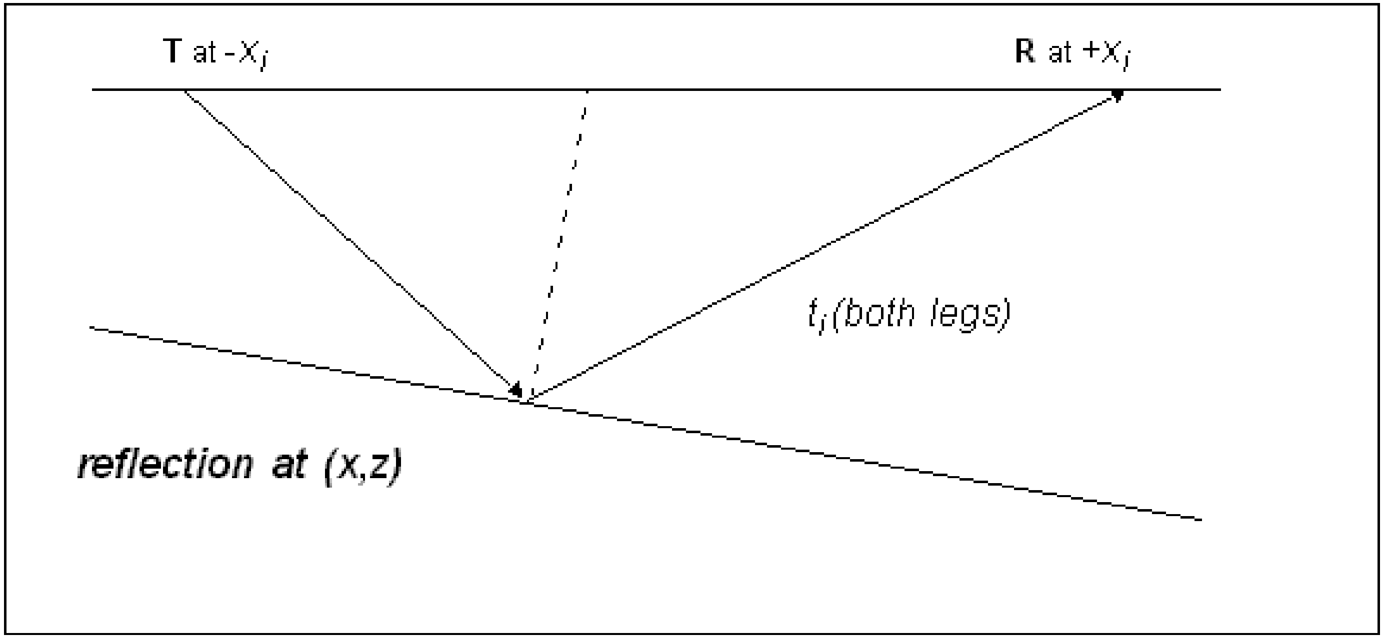
measure: $\{x_i, t_i\}$

calculate: $c_O, \alpha, z, \{\theta_i\}$

note: compare with the "mirage" effect, where you have reflection that doesn't require any reflecting surface

nonparallel layers

- acoustic time-of-flight defines an elliptical locus to which the reflecting discontinuity is tangent
- there is usually only one physically reasonable line that is tangent to two such ellipses
  - so if *c* is known, two $\{x_i, t_i\}$ pairs fix the depth and angle of inclination of the reflecting plane
  - an additional pair will resolve any ambiguity
  - when *c* is not known in advance, an additional pair is sufficient to find both *c* and the correct reflecting plane



measure: $\{x_i, t_i\}$ for $i = 1,2,3$

calculate: c, and the line that is tangent to both ellipses

$$\frac{x^2}{a_i^2} + \frac{z^2}{b_i^2} = 1 \quad \text{where } a_i^{\,2} = c^2\, t_i^{\,2} \text{ and } b_i^{\,2} = a_i^{\,2} - x_i^{\,2}$$

tactile sensors & displays

recommended reading

- classic tactile sensing articles for history:
  - Nicholls & Lee (~1990)
  - Leon Harmon (~1982)
- current robotics literature for latest gadgets
- articles cited
  - older articles on next page
  - hopefully newer articles cited in up-coming student lecture

older tactile sensing literature

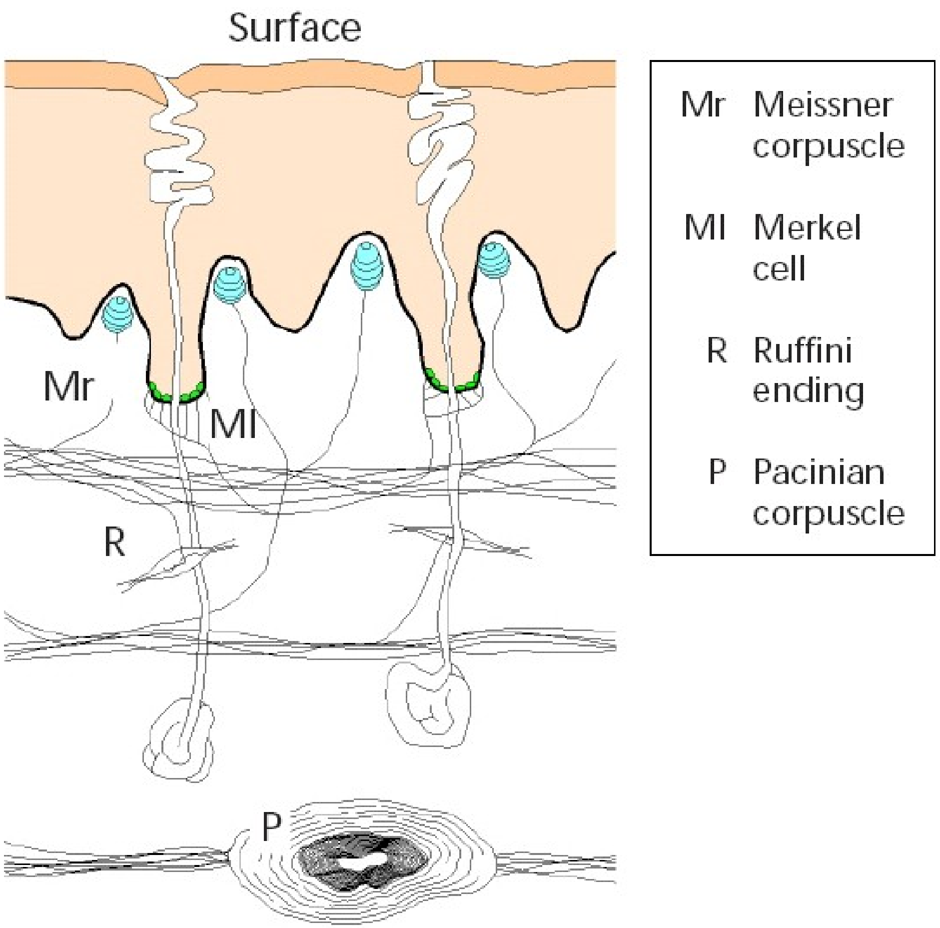
- Harmon, L.D., Automated Tactile Sensing. International Journal of Robotics Research, 1982. 1(2): p. 3-32.
- Pugh, A., Tactile and Non-Vision. Robot Sensors, ed. A. Pugh. Vol. 2. 1986, Bedford UK: IFS (Publications) Ltd and Springer-Verlag.
- Nicholls, H.R. and M.H. Lee, A Survey of Robot Tactile Sensing Technology. International Journal of Robotics Research, 1989. 8(3): p. 3-30.
- Ron Fearing: http://robotics.eecs.berkeley.edu/~ronf/tactile.html
- National Academy Press, Expanding the Vision of Sensor Materials. 1995. (Appendix A, references) http://books.nap.edu/books/0309051754/ 101.html#pagetop
- also: medical-tactile sensing (not covered explicitly here)

tactile sensing

simulating (sensors)
and
stimulating (displays)
the
human sense of **touch**

human skin tactile sensitivity

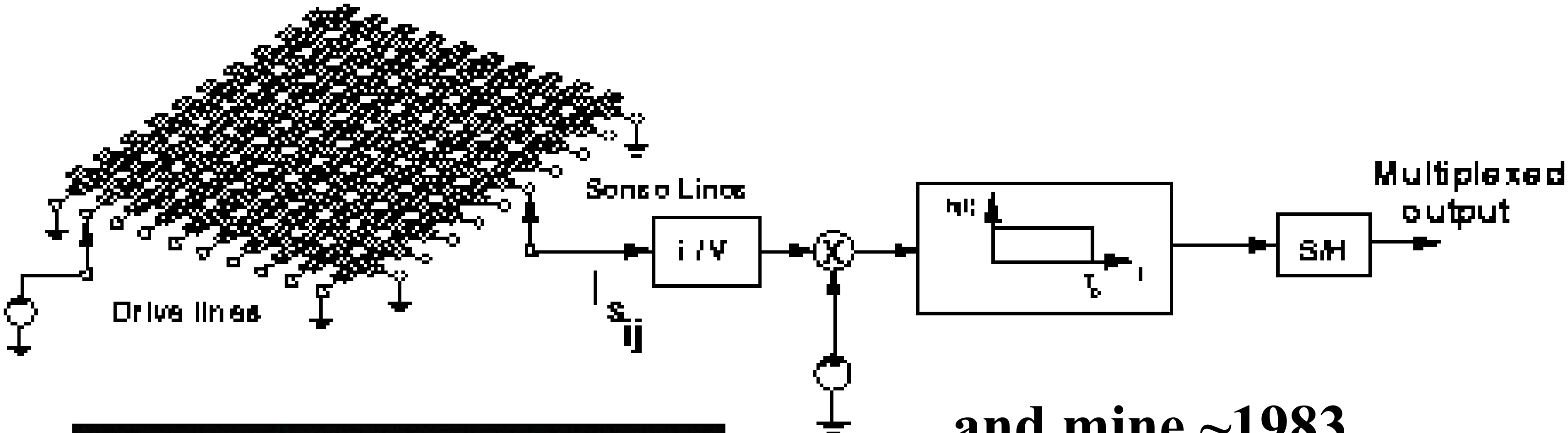
- at least four different kinds of sensor cells
- different spatial and frequency sensitivities



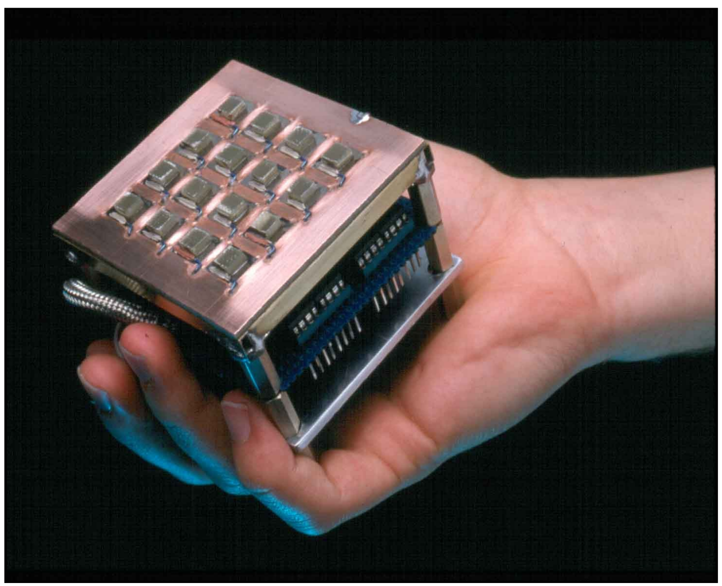
speculative specifications fingers

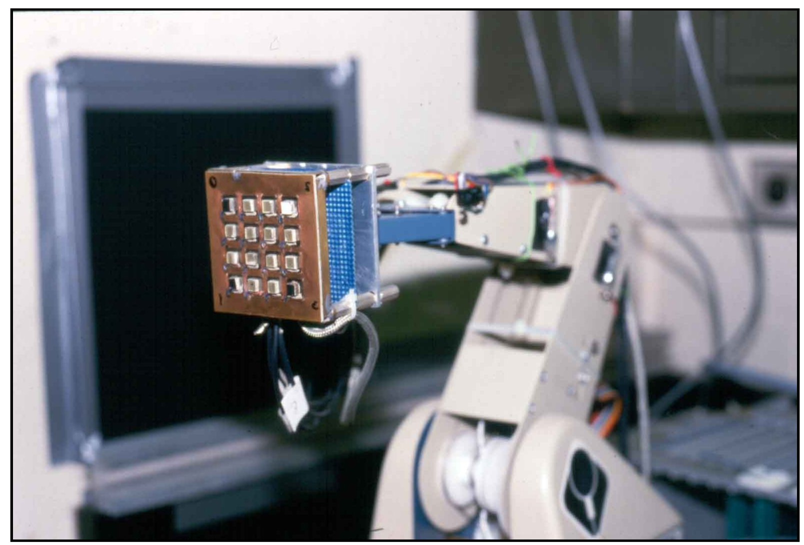
- “ideal stimulator” would provide 50 N/cm^2 peak pressure, 4 mm stroke, and 25 Hz BW (Fearing)
- skin acts like a spatial low-pass filter
  - when we handle flexible materials (fabric, paper) we sense the pressure variation across the finger tip
- fingertip mechanoreceptor bandwidth ~30 Hz
- density 70 cm^{-2} (resolve ~1.2 mm between points)
- finger curvature, thermal properties, and other environmental factors seem critical to teletaction

conceptual tactile sensor array (Fearing)



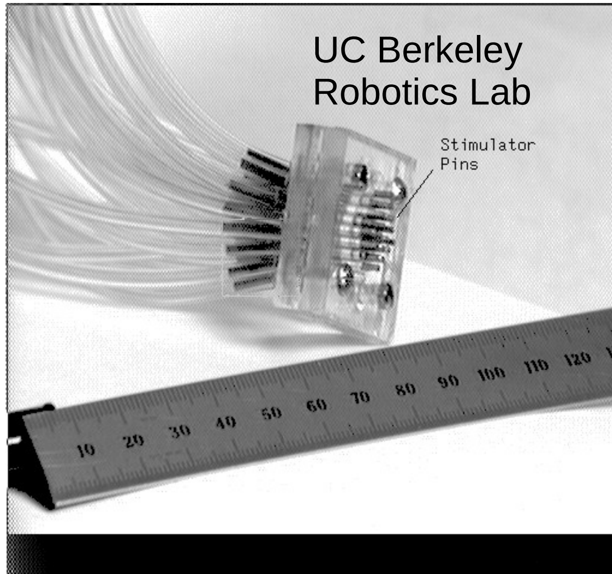
and mine ~1983



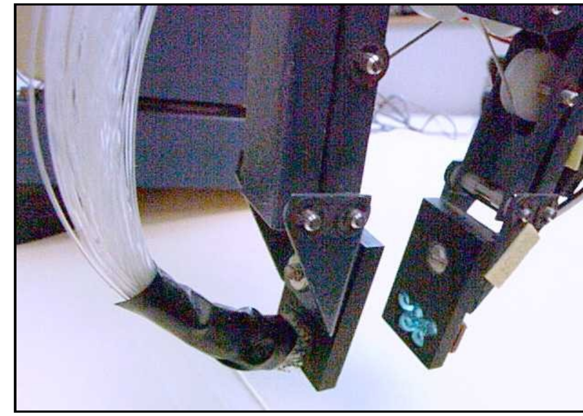


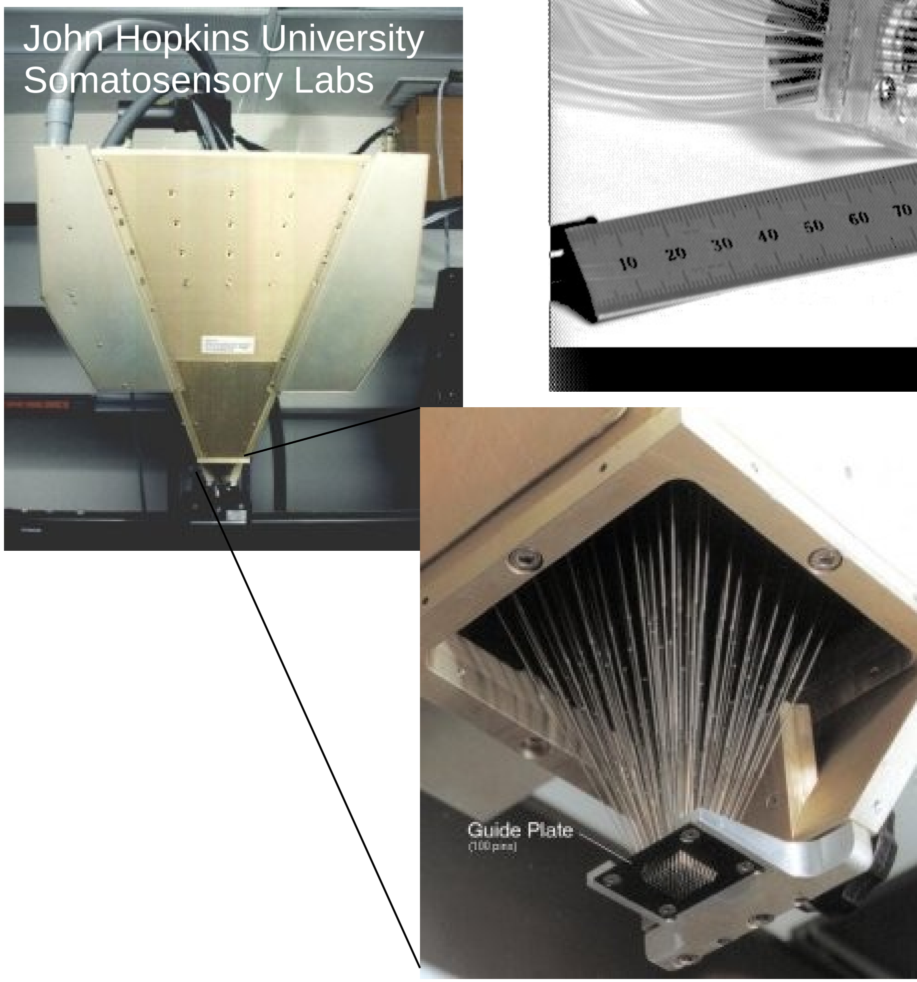
current haptic interfaces and tactile displays

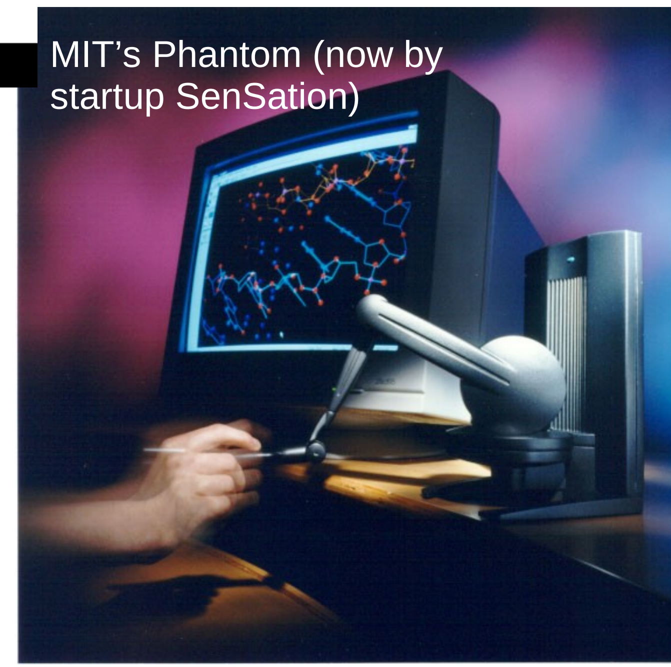
- **virtual reality**
- **people with disabilities**



and mine ~1985







tactile sensor requirements

- see the Leon Harmon articles:
  - surveyed industry, government, research people to ascertain the specs they *thought* tactile sensing for robotic assembly etc. required
  - (but how did they know??)
- "blue sky" and practical requirements:
  - skin-like sensors, hand-like actuators, low-level processing
  - practical specifications summarized in Nicholls article
- financed by Lord Corporation
  - defunct product: tactile sensor array for robotics

a solution in search of a problem?

- identification or location?
- agree with Nicholls and Lee’s conclusion that vision is well-developed and probably fundamentally better for identification ... better role for tactile is precise relative location
- difficulty & importance of slip sensing
  - literature often mentions “incipient slip”, but it is never clear what it means
  - coefficient of friction decreases once slip begins, making recovery difficult

real-world applications of tactile sensing

- T. Goto, T. Inoyama, K. Takeyasu (Hitachi, Japan): Precise Insert Operation by Tactile-Controlled Robot (in the Pugh book, 1986!!)
  - "The HI-T-HAND Expert-1 assembly robot has now been completed. Its delicate tactile control is capable of inserting a shaft into a hole with a clearance of 20 micrometers, faster and more dexterously than in a human operation. It is impossible for conventional robots and automatic assembling machines to perform such operations of precision insertion. Accordingly, such operations have been left for man's hand to perform. Now, however, the sequence controller makes it possible, without the use of a computer for robots to perform certain of these functions."
- this is the ONLY one I know!

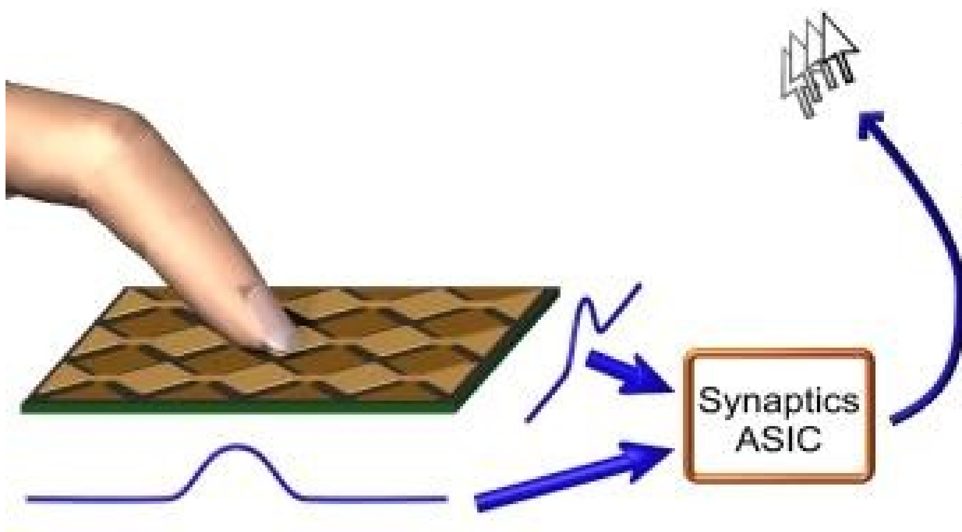
technologies for tactile sensing

you name it, IT'S BEEN TRIED!

- momentary switch contact
- spring + LVDT or some such analog pressure measurement
  - including MEMS techniques, e.g., strain gauges on diaphragms
- force sensitive resistor (with or without built-in mechanical threshold)
- capacitative or optical measurements of surface deformation
- liquid crystal (color &/or opacity changes with deformation)

- total internal reflection (e.g., for fingerprints)
- phonograph needle for slip/vibration *(do you know what it is?)*
- thermistors etc for temperature/thermal conductivity etc
- piezoelectric, pyroelectric (e.g., PVDF)
- etc etc etc

- most commonplace, maybe most promising: “touch pad” capacitive arrays http://www.synaptics.com/technology/cps.cfm
- exception to the generalization:
this is a “proximity” vs. a “pressure” sensor!



a good example of the principle that if Y (in the environment) makes X (a resistor, capacitor, etc) BAD, then a BAD design for X can be exploited to as a GOOD sensor for Y

a little philosophy: the synergy of sensor & display development

tactile displays THEN tactile sensors?

- television and telephone: analogy
  - contrived sensor is secondary to natural display
    - make the best speaker you can ... then optimize microphone
    - make the best TV display you can ... then optimize camera
    - (until recently ... computer-understanding changes the rules ...)

- radar and sonar: contrast
  - contrived display is secondary to a trans-human sensor
    - raw data initially as peaks, wiggles, etc, in signal vs. time plot
    - human-centered displays later conceived and developed for non-experts, natural interpretation even by experts, etc

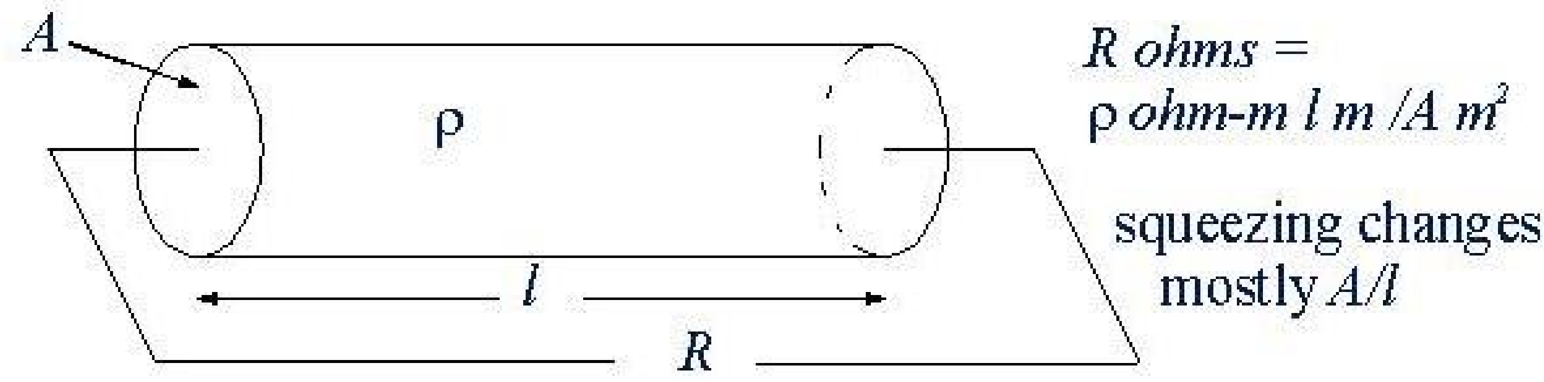
a principle?

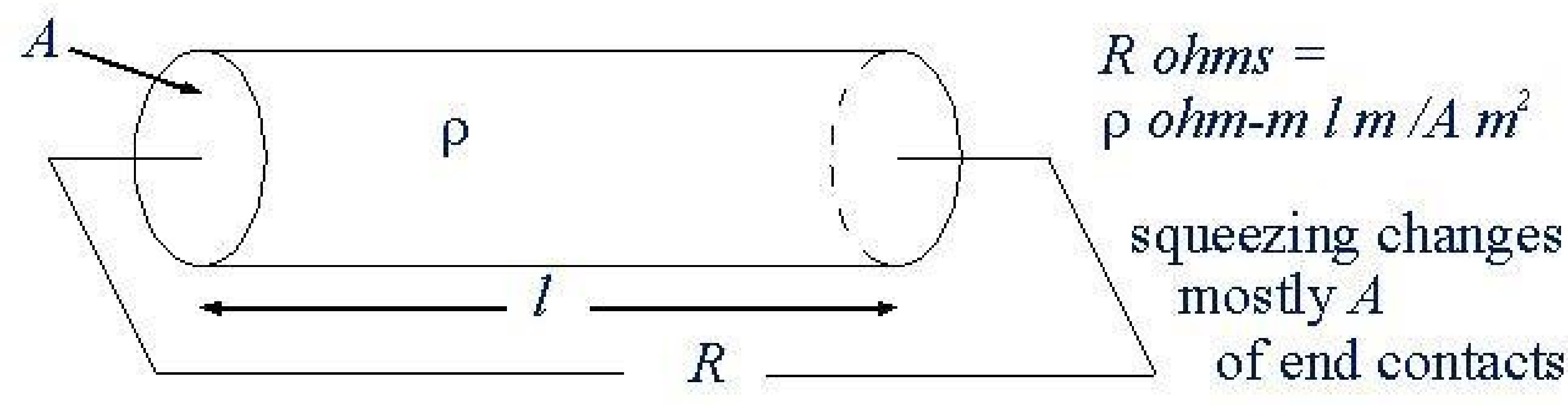
- there is no point in making a display with more resolution than your best sensor
  - in any domain:
    spatial, temporal, dynamic range, color, etc
  - (unless you have a virtual sensor that is better!)
- there is no point in making a sensor with more resolution than your best display
  - (though in many domains you can “zoom in”)
- so improvement cycles display ↔ sensor

piezo-resistive sensors

pressure sensitive resistors (PSR)

- bulk resistance vs. contact resistance





PSR magnitude

- Nicholls and Lee say few hundred to few thousand ohms is typical ...
- my experience is that common conductive foams (IC packaging etc) etc are typically 1000 - 10000 times higher ...
  - so high impedance measurement techniques must be employed
  - and time response ($\tau = RC$) can suffer

PSR noise

- no general theory (that I know)
- contact-resistance-based designs are noisy
- surface effects are noisier than volume effects
  - density of opportunities for trouble is higher in a space of lower dimensionality
    - a single defect is fatal in 1-dimension
- but depending on details of the particular design, under microscopic examination distinction may not be clear
  - bulk resistance change may be due to distortion (A/l)
  - but it can also be due to changes in inter-grain contact

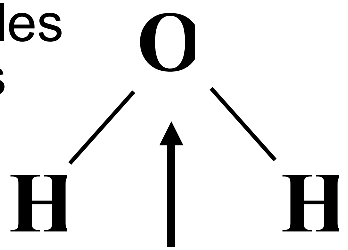
exercise

- A cylindrical resistive element is compressed or stretched in a way that does not change its basically-cylindrical shape, and does not change its volume; assuming its resistivity does not change either, derive how $\Delta R/R$ (fractional change in resistance) depends on $\Delta L/L$ (fractional change in length).

piezo-electric sensors

piezo- and pyroelectric devices

- piezo- (pressure) and pyro- (heat) electricity are always coupled
- it is due to separation of electrical charges in the material's crystalline arrangement
  - electric dipoles at the molecular level (e.g., H_2O)
  - high voltage poling to macroscopically align dipoles
  - "electrets" made by poling various waxy mixtures
- pressure → voltage (sensor)
  voltage → deformation (actuator)
- due to leakage, effect is transient
  - to stabilize, leakage is intentionally increased, making device response effectively to *dP/dt*
- high voltage + high input impedance → tiny current (hard to measure, slow to measure)



practical piezoelectric materials

- quartz (cut along particular crystal axes to maximize piezo- and minimize pyro- effects)
  - effect small but very stable
- various ceramics, e.g., ZnO, PZT(TM)
  - deposition on micro- and mini- fabricated devices
    - SAW (surface acoustic wave) devices for sure
    - MEMS devices discussed but not sure whether implemented
- plastics: polyvinylidene difluoride (PDVF, PVF_2)
  - enormous quantities are reportedly used in submarine sonar transducers
    - yeah, so why is it so expensive?

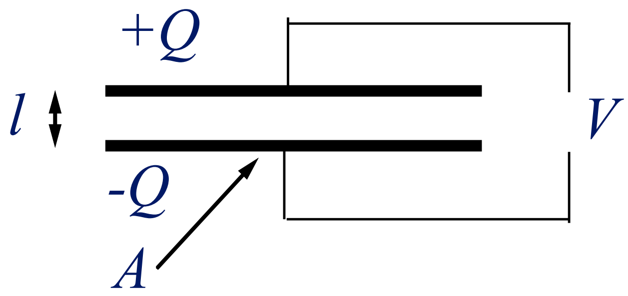
magnitude of piezoelectric effect

- easy to get tens of volts but need high input impedance measuring instrument
- can get very high voltages (enough to spark across ~ 1 mm) in response to impact
  - buy yourself a “flintless” butane lighter

capacitive sensing

capacitive devices

- "mouse pad" or "touch pad" is now ubiquitous, reliable, stable
- same geometrical factors as resistive sensors (but remember that capacitance is defined "upside down": V = L dI/dt + R I + Q/C
- actual approach is to measure distortion in "stray" capacitance
- (again) see http://www.synaptics.com/technology/cps.cfm
- many geometries, including some "finger-like" curvatures



$$V \text{ volts} = \varepsilon \text{ farad/m } A \text{ m}^2 / l \text{ m}$$

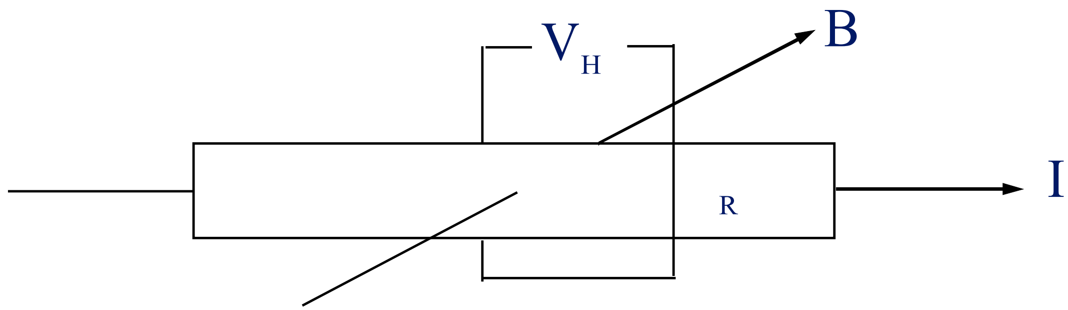
magnitude of capacitive effects

- $\mu_0 = 4\pi\ 10^{-7}$ henry/m, $\varepsilon_0 = \mu_0/c^2 = 8.85\ 10^{-12}$ farad/m
- "small capacitor" is ~ 100 pF (p = pico = 10^{-12})
- say you want to see a 1% change in capacitance
- say tactel is 1 mm^2, dielectric constant is 10
- then to get 100 pF need $l = 10\ \varepsilon_0 A / C = 10^{-6}$ m or 10^{-3} mm
- and to resolve a 1% change need to see 10^{-8} m
  - wavelength of green light is around 50×10^{-8} m
- might use multi-layer tricks to improve this
- *but the smallness of this effect probably explains why the commercial technology exploits the "stray capacitance" effect vs. pressure-induced capacitance change*
  - however: the best vacuum/gas pressure sensors are capacitive

miscellaneous tactile sensing schemes

magnetic and inductive effects

- many prototypes, probably no products
- inductive devices are more-or-less miniature LVDTs
- magnetic effects, e.g., magneto-resistance plausible
  - recent developments of “giant” and “colossal” magneto-resistance materials may hold promise, but no developments as yet ...
- slip sensing potential with dipoles oriented *within* surface
- Hall effect sensors may be the most plausible, as Hall effect switches are in common use in computer keyboards etc

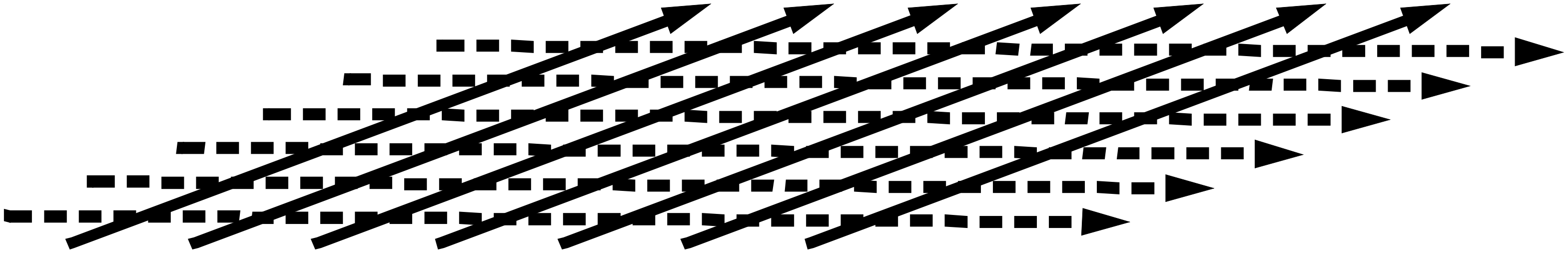


Hall effect: voltage due to deflection of current’s charge carriers

deformation of elastomers

- many mechanical, optical, and acoustic readout schemes prototyped ...
  - optical? for example, modified total internal reflection schemes (as mentioned above)
  - acoustic? Grahn @ Utah: ultrasonic measurement of compression
- typically cumbersome ... probably obsolete except as source of ideas for future MEMS implementations ...

- fiber optic schemes, e.g., Schoenwald @ Rockwell
  - seemed promising
  - potentially "fabric"- or even "skin"-like
  - but never went anywhere commercially



miscellaneous issues

“finger-like”surfaces

- for surfaces with “true gaussian curvature”, little that seems ready for prime-time ...
- R. Fearing, Int. J. Robotics Research, V. 9 #3, June 1990, p.3-23: Tactile Sensing Mechanisms (from his PhD thesis): “fingertip” (cylinder with hemispherical cap), with capacitive pressure sensor embedded in the *cylindrical (only)* part
  - 8 circumferential x 8 axial electrode array in molded rubber
  - capacitance measured at 100 kHz; scanned at 7 Hz
  - maybe cylindrical surfaces are not so bad
    - e.g., it is useful to be able to bend planar sheets
  - problems with hysteresis and creep, coupling between tactels, modelling response to fingertip loading
  - paper is good example of a complete electrical/mechanical model

related area: proximity sensing

- frustrated by lack of good “touch sensors”, there have been several (mostly Japanese) demonstrations of object identification by scanning a short range (~1 cm) “robot fingertip” proximity sensor.
- four competitive moderate-cost commercial technologies:
  - capacitive best for dielectric (insulating) materials
  - inductive best for metallic (conducting) materials
  - optical: simple transmitter-receiver pair, e.g., Radio Shack
  - acoustic: probably for somewhat longer range
- some proven but less developed and accepted ways:
  - fiber optic bundles
  - focus based methods (e.g., using CD-player components)
  - (field emission/tunneling/discharge/ etc. are a bit far out)
    - sensitive but difficult to calibrate

MEMS tactile display development (mostly CMU)

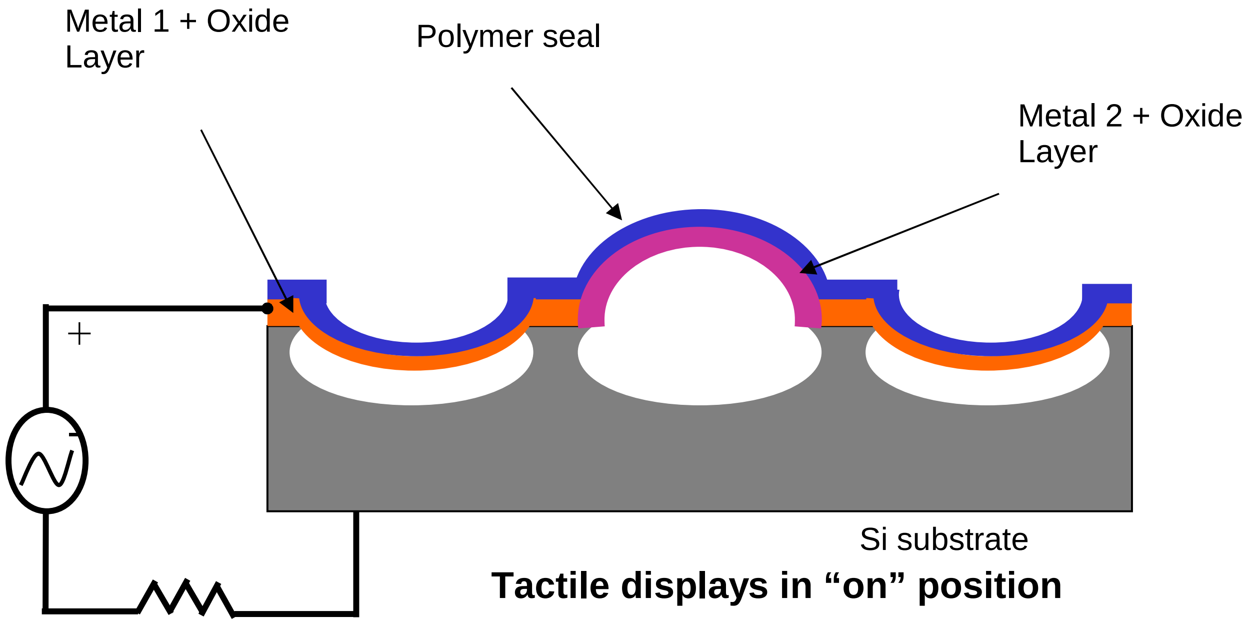
thanks to George Lopez

MEMS actuators for tactile stimulation

- two sealed chambers sharing common membrane

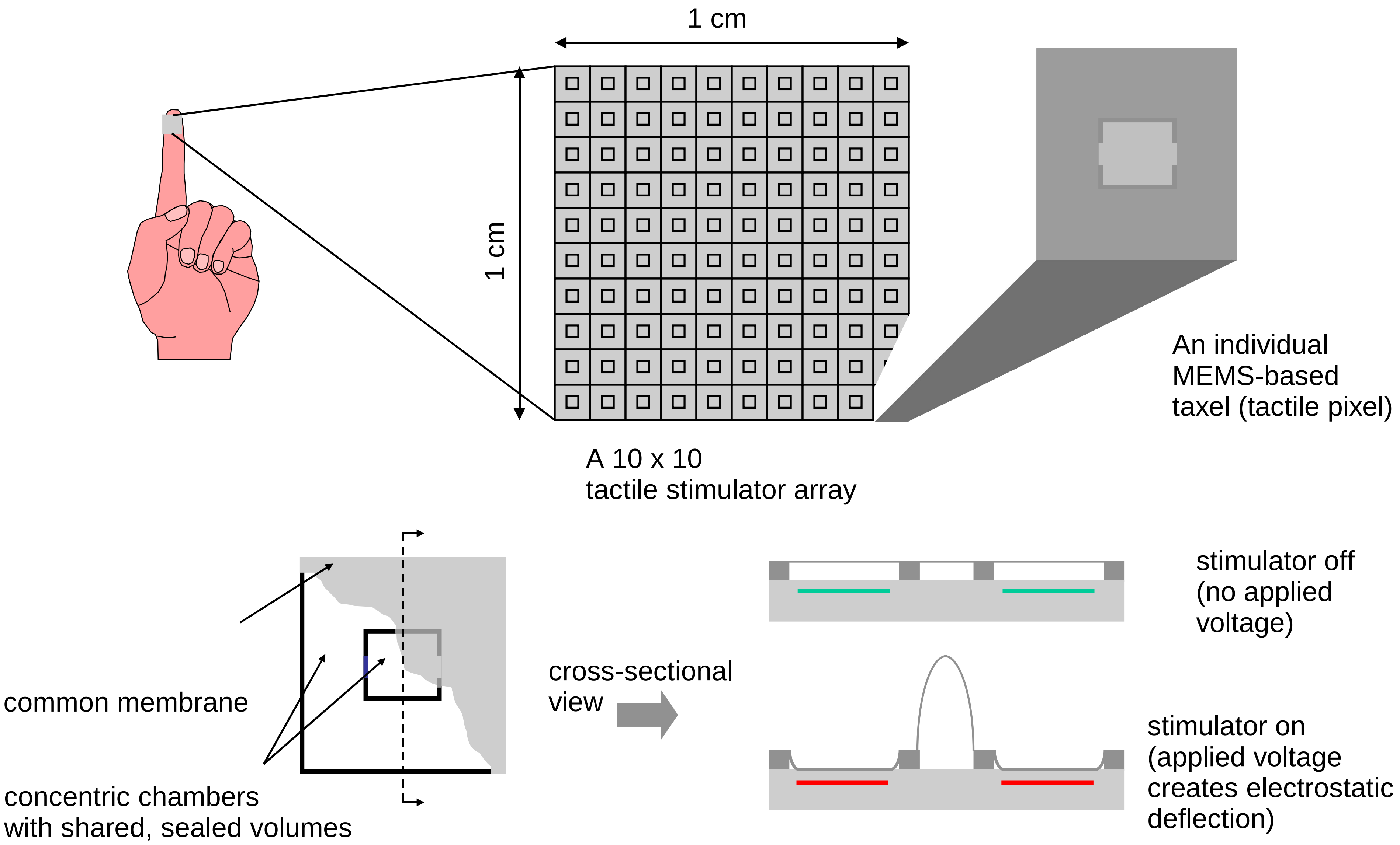
- inner chamber out-of-plane force/deflection caused by electrostatic compression of outer chamber

- move towards integrated actuator and control, all “on-chip”; experiment now with CMOS membranes

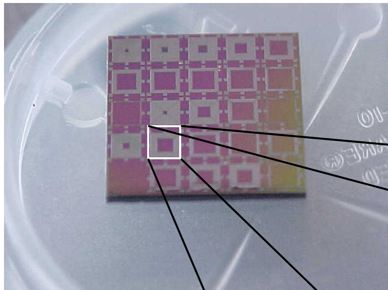


Tactile displays in “on” position

MEMS tactile stimulator array concept

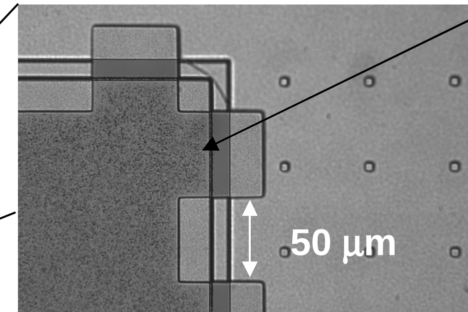


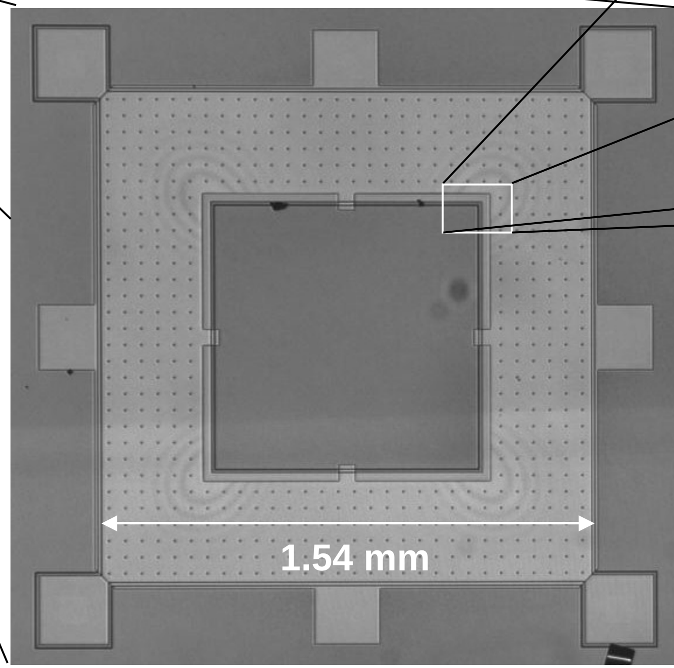
test taxel chip fabrication results



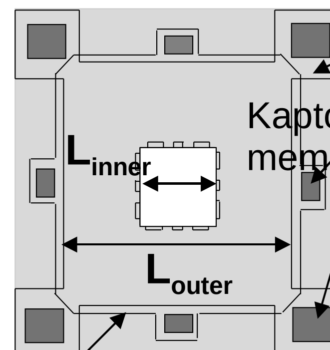
tactile stimulator test chip with 11 different inner radii

openings between inner and outer chamber volume





bottom electrode of actuator (polysilicon)



Kapton common membrane (post-fab)

upper electrode of actuator (polysilicon)

long term goal: build on flexible silicon membranes