Bioengineering 280A
Principles of Biomedical Imaging

Fall Quarter 2009
Ultrasound Lecture 1

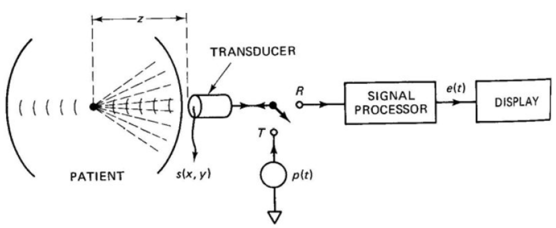
Acuson Sequoia

Sonosite 180

From Suetens 2002

See also: http://www.youtube.com/watch?v=7gU1uSlxKDs

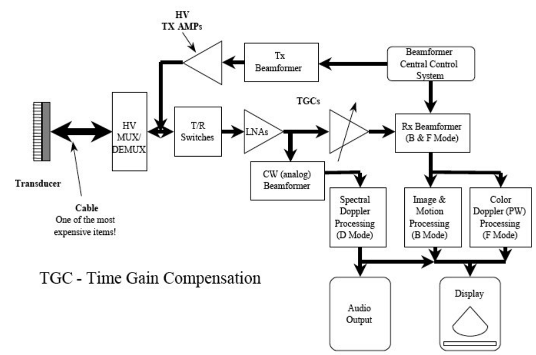
Basic System



Echo occurs at $t=2z/c$ where c is approximately 1500 m/s or 1.5 mm/μs

Macovski 1983

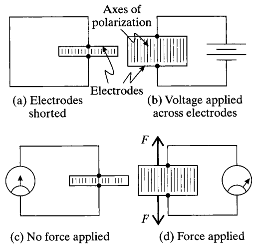
Basic System

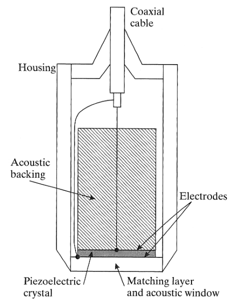


TGC - Time Gain Compensation

Brunner 2002

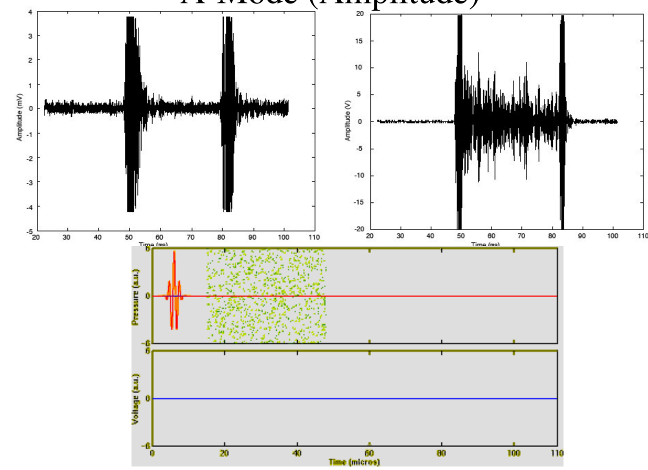
Transducer





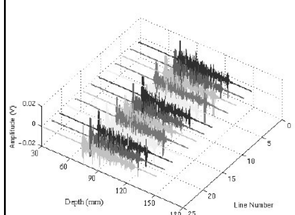
Prince and Links 2006

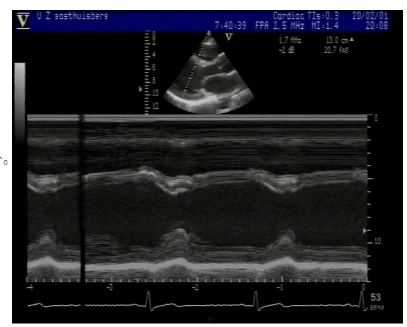
A-Mode (Amplitude)



Seutens 2002

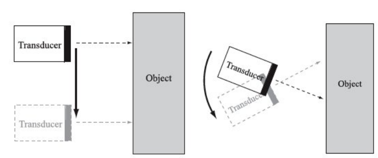
M-Mode (Motion)



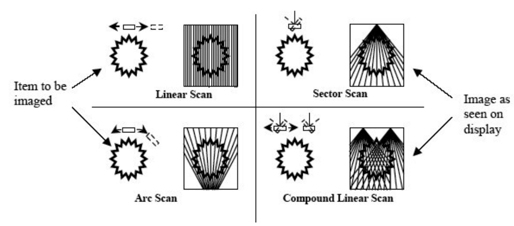


Seutens 2002

B-Mode (Brightness)

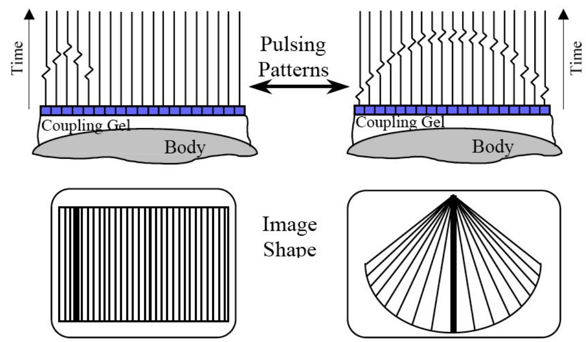


Seutens 2002



Brunner 2002

B-Mode (Brightness)



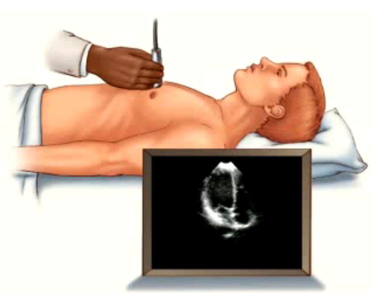
Brunner 2002

B-Mode

2002

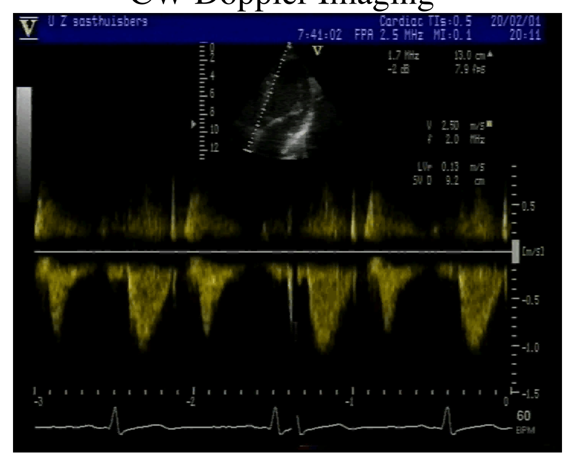
Mayo Clinic

B-Mode



Credit: Mayo Clinic

CW Doppler Imaging



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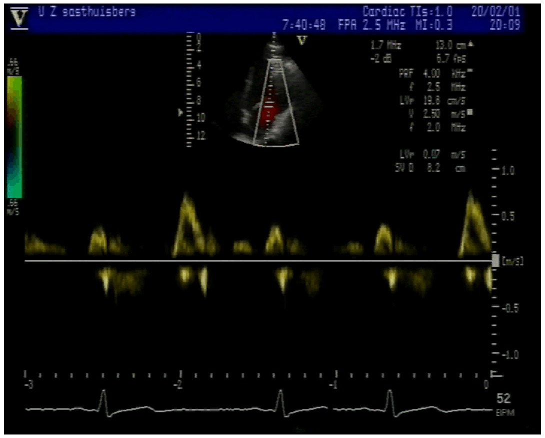
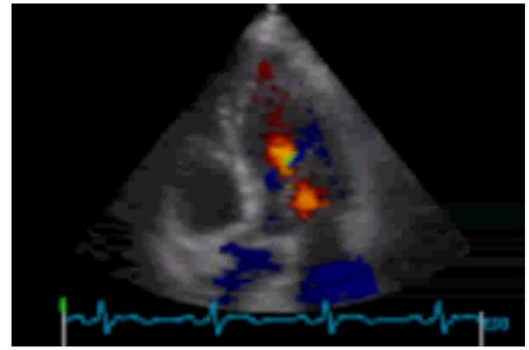
PW Doppler Imaging



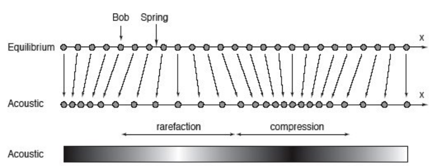
Seutens 2002

Color Doppler Imaging



Seutens 2002

Acoustic Waves



Suetens 2002

Speed of Sound

$$c = \sqrt{\frac{1}{\kappa\rho}} \quad [\mathrm{m\ s^{-1}}]$$

$$\kappa = \text{ compressibility } \quad [\mathrm{m\ s^{2}\ kg^{-1}}] = [1/\mathrm{Pascal}]$$

$$\rho = \text{density } \quad [\mathrm{kg\ m^{-3}}]$$

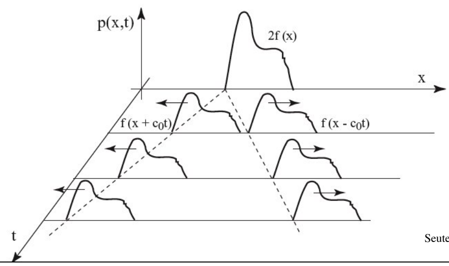
Material	Density	Speed m/s
Air	1.2	330
Water	1000	1480
Bone	1380-1810	4080
Fat	920	1450
Liver	1060	1570

Acoustic Wave Equation

$$\nabla^2 p = \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right) p = \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2}$$

Solutions are of the form

$$p(x,t) = A_1 f_1(x - ct) + A_2 f_2(x + ct)$$



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Plane Waves

$$p(z,t) = \cos(k(z - ct))$$
$$= \cos\left(\frac{2\pi}{\lambda}(z - ct)\right)$$
$$= \cos\left(\frac{2\pi f}{c}(z - ct)\right)$$
$$= \cos(2\pi f(z/c - t))$$

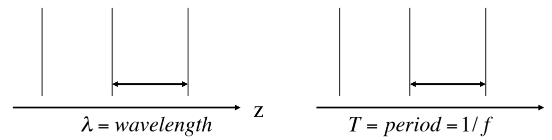
$$p(z,t) = \exp(jk(z - ct))$$

$$k = wavenumber = \frac{2\pi}{\lambda} = 2\pi k_z$$

$$\lambda = wavelength = \frac{c}{f}$$

$f = frequency$ [cycles/sec]

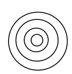
$$T = period = \frac{1}{f}$$



Spherical Waves

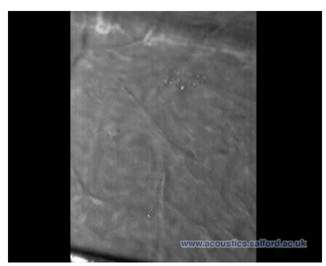
Outward wave ↘ ↙ Inward wave

$$p(r,t) = \frac{1}{r}\phi(t - r/c) + \frac{1}{r}\phi(t + r/c)$$

Outward wave 

$$p(r,t) = \frac{1}{r}\exp(j2\pi f(t - r/c))$$

Note: The phase depends on both space and time. At a given time, wavefront occurs at r = ct. At a given location, wavefront arrives at t = r/c.



Impedance

$$\text{Impedance } Z = \frac{\text{Pressure}}{\text{Velocity}} = \frac{P}{v} = \rho c = \sqrt{\frac{\rho}{\kappa}}$$

density kg/m^3

speed of sound
Brain 1541 m/s
Liver 1549
Skull bone 4080 m/s
Water 1480 m/s

Note: particle velocity and speed of sound are not the same!

Impedance

$$Z = \rho c = \sqrt{\frac{\rho}{\kappa}}$$

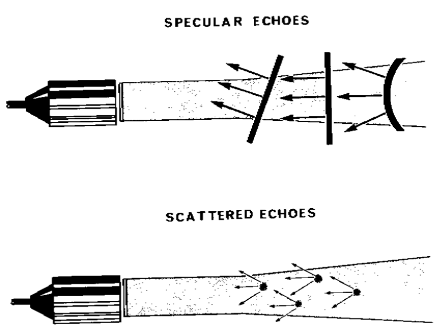
Material	Density	Speed m/s	Z (kg/m^2/s)
Air	1.2	330	0.0004
Water	1000	1480	1.5
Bone	1380-1810	4080	3.75-7.38
Fat	920	1450	1.35
Liver	1060	1570	1.64-1.68

Acoustic Intensity

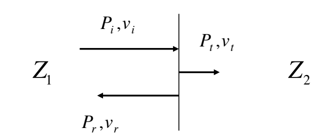
$$I = pv$$
$$= \frac{p^2}{Z}$$

Also called acoustic energy flux.
Analogous to electric power

Echos



Specular Reflection



Material	Reflectivity
Brain-skull	0.66
Fat-muscle	0.10
Muscle-blood	0.03
Soft-tissue-air	.9995

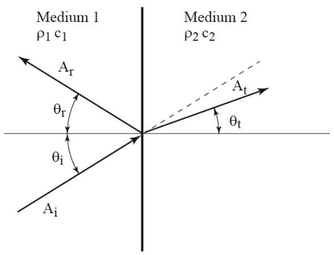
$v_i - v_r = v_t$ (velocity boundary condition)

$$\frac{P_i}{Z_1} - \frac{P_r}{Z_1} = \frac{P_t}{Z_2}$$

$P_i + P_r = P_t$ (pressure boundary condition)

$$R = \frac{P_r}{P_i} = \frac{Z_2 - Z_1}{Z_2 + Z_1} \approx \frac{\Delta Z}{Z_0}$$

Reflection and Refraction



Snell's Law

$$\frac{\sin\theta_i}{c_1} = \frac{\sin\theta_r}{c_1} = \frac{\sin\theta_t}{c_2}$$

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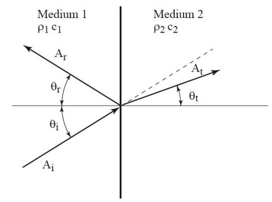
Reflection and Refraction



$$v_i\cos\theta_i = v_r\cos\theta_r + v_t\cos\theta_t$$

$$\frac{p_i}{Z_1}\cos\theta_i = \frac{p_r}{Z_1}\cos\theta_r + \frac{p_t}{Z_2}\cos\theta_t$$

$$p_i + p_r = p_t$$

Pressure Reflectivity $$R = \frac{p_r}{p_i} = \frac{Z_2\cos\theta_i - Z_1\cos\theta_t}{Z_2\cos\theta_i + Z_1\cos\theta_t}$$

Pressure Transmittivity $$T = \frac{p_t}{p_i} = \frac{2Z_2\cos\theta_i}{Z_2\cos\theta_i + Z_1\cos\theta_t}$$

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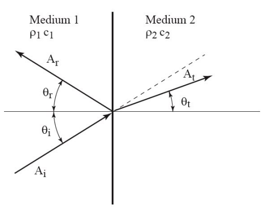
Reflection and Refraction



Intensity Reflectivity $$R_I = \frac{I_r}{I_i} = \frac{p_r^2}{p_i^2} = \left(\frac{Z_2\cos\theta_i - Z_1\cos\theta_t}{Z_2\cos\theta_i + Z_1\cos\theta_t}\right)^2$$

Intensity Transmittivity $$T_I = \frac{I_t}{I_i} = \frac{p_t^2 Z_1}{p_i^2 Z_2} = \frac{4Z_1 Z_2\cos^2\theta_i}{\left(Z_2\cos\theta_i + Z_1\cos\theta_t\right)^2}$$

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Example

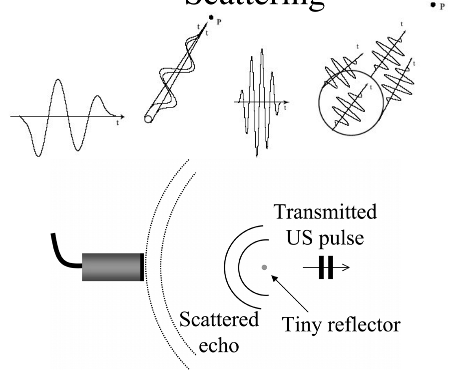
Example : Fat/liver interface at normal incidence

$Z_{fat} = 1.35\times10^{-6}$ kg m^{-2} s^{-1}

$Z_{liver} = 1.66\times10^{-6}$kg m^{-2} s^{-1}

$$R_I = \left(\frac{Z_{liver} - Z_{fat}}{Z_{liver} + Z_{fat}}\right)^2 = 0.103$$

Scattering



Point scatterers retransmit the incident wave equally in all direction (e.g. isotropic scattering).

Attenuation

Loss of acoustic energy during propagation.

Conversion of acoustic energy into heat.

$$p(z,t) = A_z f(t - c/z)$$
$$= A_0 \exp(-\mu_a z) f(t - c/z)$$

Amplitude attenuation factor

$$\mu_a = -\frac{1}{z} \ln \frac{A_z}{A_0} \quad : \text{ units } = \text{ nepers/cm}$$

$$\alpha = -20 \frac{1}{z} \log_{10} \frac{A_z}{A_0} = 20 \mu_a \log_{10}(e) \approx 8.7 \mu_a \quad : \text{ dB/cm}$$

Attenuation coefficient

Attenuation

$$\alpha(f) = \alpha_0 f^n$$

For frequencies used in medical ultrasound, $n \approx 1$.

$$\alpha(f) \approx \alpha_0 f$$

Material	α_0 [dB/cm/MHz]
fat	0.63
liver	0.94
Cardiac muscle	1.8
bone	20.0

Example

Example: Fat at 5 MHz

Attenuation coefficient $= 5\text{MHz} \times 0.63$ dB/cm/MHz

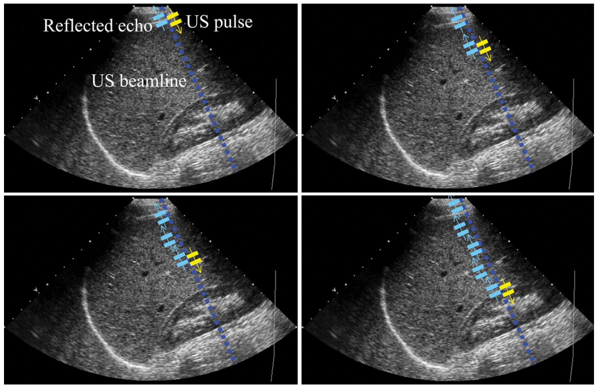
$= 3.15$dB/cm

After 4 cm, attenuation $= 4 * 3.15 = 12.6$ dB

Relative amplitude is $10^{(-12.6/20)} = 0.2344$

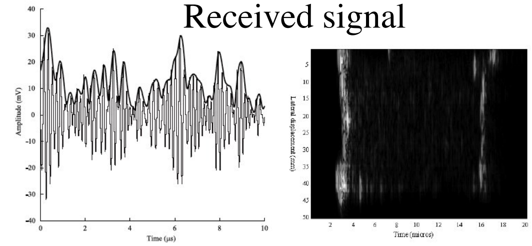
Recall dB $\equiv 20\log_{10}(A_z / A_0)$

Received signal



http://radiographics.rsnajnls.org/content/vol23/issue4/images/large/g03jl25c1x.jpeg

Received signal



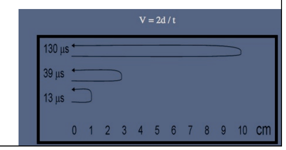
$$e(t) = K\int\int\int \frac{e^{-2\alpha z}}{z} R(x,y,z)s(x,y)\,p(t-2z/c)\,dxdydz$$

Attenuation

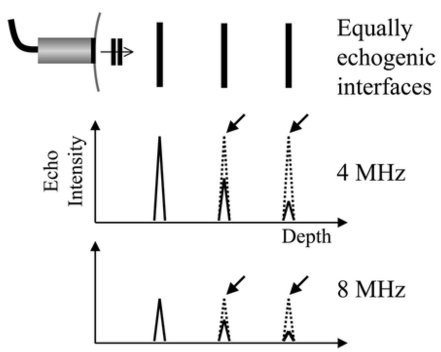
Reflection/Scattering

Beam width

Pulse



Attenuation Correction



Attenuation Correction and Signal Equation

$$e(t) = K\int\int\int \frac{e^{-2\alpha z}}{z} R(x,y,z)s(x,y)\,p(t-2z/c)\,dxdydz$$

$$\approx K\frac{e^{-\alpha ct}}{ct/2}\int\int\int R(x,y,z)s(x,y)\,p(t-2z/c)\,dxdydz$$

$$e_c(t) = cte^{\alpha ct}e(t)$$

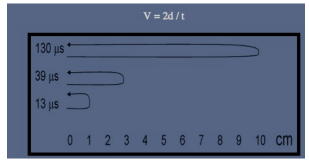
$$\approx K\int\int\int R(x,y,z)s(x,y)\,p(t-2z/c)\,dxdydz$$

$$= \frac{c}{2}\int\int\int R(x,y,c\tau/2)s(x,y)\,p(t-\tau)\,dxdyd\tau$$

Depth Response

Depth response

$$p(t-2z_0/c) = p(2z/c - 2z_0/c) = p\left(\frac{2(z-z_0)}{c}\right)$$

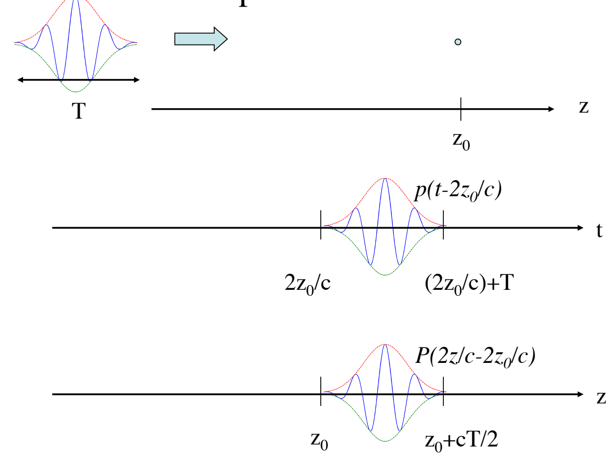


Therefore impulse response is simply

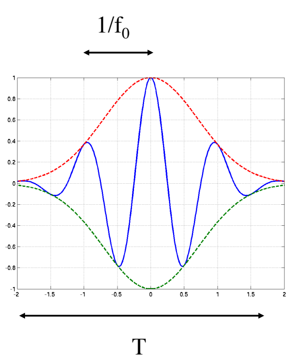
$p(t)$ in the time domain or

$p(2z/c)$ in the spatial domain

Depth Resolution



Depth Resolution



$p(t) = p(2z/c)$ determines the depth resolution

Pulses are of the form $a(t)\cos(2\pi f_0 t + \theta)$ where $a(t)$ is the envelope function and f_0 is the resonant frequency of the transducer.

The duration of T of $a(t)$ is typically chosen to be about 2 or 3 periods (e.g. $T = 3/f_0$).
If the duration is too short, the bandwidth of the pulse will be very large and much of its power will be attenuated.

The depth resolution is approximately
$\Delta z = cT/2 \approx 1.5c/f_0 = 1.5\lambda$.

Depth Resolution

The depth resolution is approximately $\Delta z = cT/2 \approx 1.5c/f_0 = 1.5\lambda$.

Example:

For $f_0 = 5$ MHz, $\lambda = c/f = (1500 m/s)/(5\times 10^6 Hz) = 0.3mm$

$\Delta z = 1.5\lambda = 0.45$ mm

Trade-off

Higher $f_0 \Rightarrow$ Smaller $\Delta z \Rightarrow$ but more attenuation

Example: Assume 1dB/cm/MHz

For 10 cm depth, 20 cm roundtrip path length.

At 1 MHz 20 dB of attenuation $\Rightarrow$ Attenuation = 0.1

At 10 MHz 200 dB of attenuation $\Rightarrow$ Attenuation = $1\text{x}10^{-10}$

Depth of Penetration

Assume system can handle L dB of loss, then

$$L = 20\log_{10}\left(\frac{A_z}{A_0}\right)$$

We also have the definition

$$\alpha = -\frac{1}{z}20\log_{10}\left(\frac{A_z}{A_0}\right)$$

and the approximation

$$\alpha = \alpha_0 f$$

Total range a wave can travel before attenuation L is

$$z = \frac{L}{\alpha_0 f}$$

Depth of penetration is

$$d_p = \frac{L}{2\alpha_0 f}$$

Depth of Penetration

Assume L = 80 dB; α_0= 1dB/cm/MHz

Frequency (MHz)	Depth of Penetration(cm)
1	40
2	20
3	13
5	8
10	4
20	2

Pulse Repetition and Frame Rate

Need to wait for echoes to return before transmitting new pulse

Pulse repetition interval is

$$T_R \geq \frac{2d_p}{c}$$

Pulse repetition rate is

$$f_R = \frac{1}{T_R}$$

If N pulses are required to form an image, then the frame rate is

$$F = \frac{1}{NT_R}$$

Example

$N = 256,\ L = 80dB,\ c = 1540m/s,\ \alpha_0 = 1dB/cm/MHz$

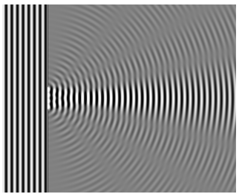
What frequency should be used to achieve a frame rate of 15 frame/sec?

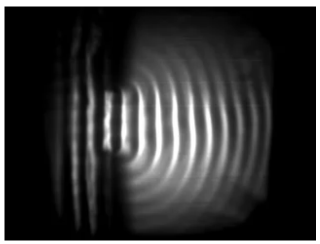
$$T_R = \frac{1}{FN} = 0.26ms$$

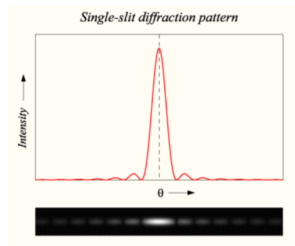
$$T_R \geq \frac{2d_p}{c} = \frac{L}{\alpha_0 fc}$$

$$f \geq \frac{L}{acT_R} = 1.99MHz$$

Single-slit Diffraction



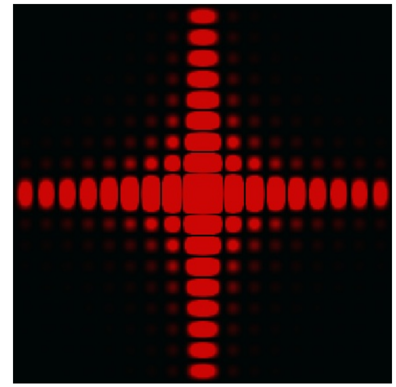




Source:wikipedia

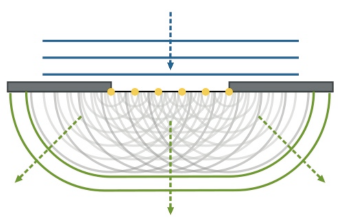
http://video.google.com/videoplay?docid=4570787435193654614&ei=aMwJS6iTFJ3KqQLp76mSDg&hl=en#

Square Aperture Diffraction



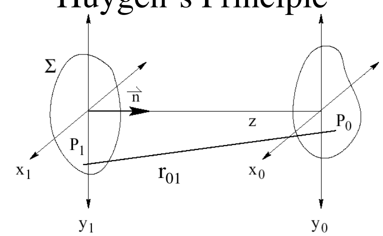
Source:wikipedia

Huygen's Principle



Source:wikipedia

Huygen's Principle



Aperture function $U(x_1, y_1)$

Field amplitude $U(x_0, y_0)$

Wavenumber $k = \frac{2\pi}{\lambda}$

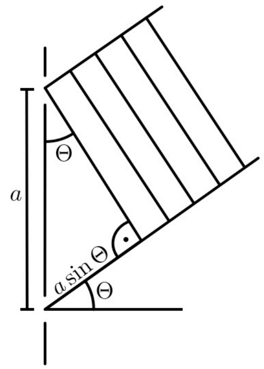
$$U(P_0) = \iint_{\Sigma} h(P_0, P_1) U(P_1) ds$$

$$\text{where } h(P_0, P_1) = \frac{1}{j\lambda} \frac{\exp(jkr_{01})}{r_{01}} \cos(\vec{n}, \vec{r}_{01})$$

Obliquity Factor

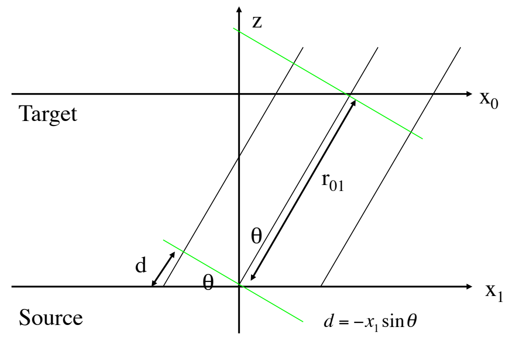
Anderson and Trahey 2000

Two-Slit Interference



Source:wikipedia

Plane Wave (Fraunhofer) Approximation



$d = -x_1 \sin\theta$

$\sin\theta = \frac{x_0}{r_{01}} \approx \frac{x_0}{z}$

$d \approx -\frac{x_0 x_1}{z}$

Assume overall distance for phase calculation is approximately z+d

Plane Wave Approximation

$$\frac{1}{r}\exp(jkr) \approx \frac{1}{z}\exp\big(jk(z+d)\big) = \frac{1}{z}\exp\left(j\frac{2\pi}{\lambda}\left(z - \frac{x_0 x_1}{z}\right)\right)$$

$$U(x_0) = \int_{-\infty}^{\infty} s(x_1)\frac{1}{r}\exp(jkr)dx_1$$

$$\approx \int_{-\infty}^{\infty} s(x_1)\frac{1}{z}\exp\left(j\frac{2\pi}{\lambda}\left(z - \frac{x_0 x_1}{z}\right)\right)dx_1$$

$$= \frac{1}{z}\exp\left(j\frac{2\pi z}{\lambda}\right)\int_{-\infty}^{\infty} s(x_1)\exp\left(-\frac{j2\pi x_0 x_1}{\lambda z}\right)dx_1$$

$$= \frac{1}{z}\exp\left(j\frac{2\pi z}{\lambda}\right)\int_{-\infty}^{\infty} s(x_1)\exp\left(-j2\pi k_x x_1\right)dx_1$$

$$= \frac{1}{z}\exp\left(j\frac{2\pi z}{\lambda}\right)F\big[s(x)\big]\Big|_{k_x = \frac{x_0}{\lambda z}}$$

Plane Wave Approximation

In general

$$U(x_0, y_0) = \frac{1}{z}\exp\left(j\frac{2\pi z}{\lambda}\right)F\big[s(x,y)\big]\Big|_{k_x = \frac{x_0}{\lambda z}, k_y = \frac{y_0}{\lambda z}}$$

Example

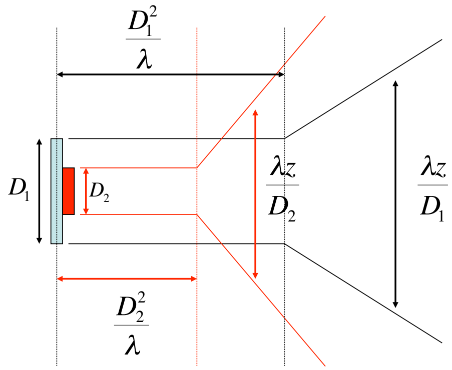
$$s(x,y) = rect(x/D)rect(y/D)$$

$$U(x_0, y_0) = \frac{1}{z}\exp(jkz)D^2 \operatorname{sinc}\left(Dk_x\right)\operatorname{sinc}\left(Dk_y\right)$$

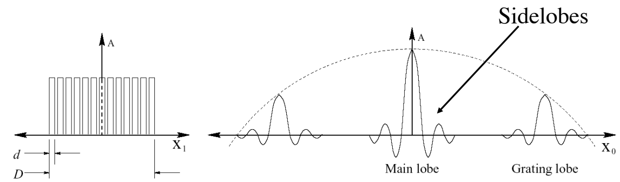
$$= \frac{1}{z}\exp(jkz)D^2 \operatorname{sinc}\left(D\frac{x_0}{\lambda z}\right)\operatorname{sinc}\left(Dk_y\frac{y_0}{\lambda z}\right)$$

Zeros occur at $x_0 = \frac{n\lambda z}{D}$ and $y_0 = \frac{n\lambda z}{D}$

Beamwidth of the sinc function is $\frac{\lambda z}{D}$



Example



$$rect\left(\frac{x}{D}\right)\left[rect\left(\frac{x}{d}\right) * \frac{1}{d} comb\left(\frac{x}{d}\right)\right] \Leftrightarrow D\,\mathrm{sin}c(Dk_x) * \left[d\,\mathrm{sin}c(dk_x) comb(dk_x)\right]$$

Question: What should we do to reduce the sidelobes?

Anderson and Trahey 2000