



UNIVERSITY
OF OSLO

INF-GEO 4310 Imaging

Introduction

Sverre Holm

DEPARTMENT OF INFORMATICS



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Short description

- Since time immemorial man has done imaging using his senses. Modern technology now gives us new opportunities for imaging.
- Examples are the human body, the surface of the earth, the sea floor, or oil reservoirs under the sea floor. Imaging is the science of creating images in different media and with different methods.
- This course uses simple laboratory exercises and problem solving to introduce various imaging methods. The emphasis is on explaining basic principles.
- In addition the course will survey the similarities between methods, and show how simple physical principles are used to create various forms of images.

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What will you learn?

The objective is to give an introduction to imaging:

- Get a cross-disciplinary understanding of imaging.
- Know the various physical principles for imaging and how they are used in various applications.
- Get a practical introduction to imaging through laboratory exercises
- Examples of applications that will be covered are:
 - optical imaging (sight, binoculars, telescope, earth observation satellites),
 - radar
 - imaging in medicine with computer tomography (CT), magnetic resonance (MR), positron emission tomography (PET) and ultrasound
 - imaging of the sea floor and fish using sonar
 - seismology for mapping of earthquakes
 - mapping of oil reservoirs with seismics



The course builds on

- MAT1100 - Calculus
- INF1000 – Basic programming
 - or INF1100 – Basic programming for scientific applications



Imaging

- <http://www.uio.no/studier/emner/matnat/ifi/INF-GEO4310/>
- Lectures: Thursday 09:15 -12:00, Seminar room 605 Veglaboratoriet
- Problem solving: Wednesday 10:15-12:15, Informatikkbygningen
 - Problems based on e.g. exams from previous years



Topics per week

- Introduction
- Geometrical optics I
- Geometrical optics II
- Radar
- Remote sensing I
- Remote sensing II
- Sonar
- Medical Ultrasound
- Acoustic Imaging
- Seismics I
- Seismics II
- Seismology
- Medical: CT, MR
- Summing it all up



Problem solving

- Some mandatory exercises:
 - Geometrical optics
 - Remote sensing
 - Sonar
 - Ultrasound
 - Seismics/seismology
- Excursions
 - Medical Ultrasound (GE Vingmed Ultrasound)
 - Medical imaging (Interventional Centre) ?
- Most of the remaining Wednesdays will be used for problem solving



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Orion's Belt

- Den ene av de 4 veggskiverelieffene, "Orions belte", til Bård Breivik som skal monteres i IFI2 er fremvist under Beijing Biennale i National Art Museum of China nå under OL. Verket måler omlag 6 x 7 meter og skal etter utstillingen skipes til Norge og lagres i påvente av montering i IFI2.
- Vi har fått rapporter fra nordmenn som har sett utstillingen i Beijing at verket fremstår som det mest imponerende og bemerkelsesverdige på hele den internasjonale utstillingen.
- Det blir totalt 4 slike verk på IFI2 og flere av dem er utformet i samarbeid med DSB-gruppen – Fritz Albrechtsen
- Jeg vedlegger et foto fra Beijing som er tatt av en bekjent av IFI2-arkitekten. Det finnes også et lite foto med selveste Sonja foran verket på UD's nettside her:
<http://www.norway.cn/culture/Exhibitions/The+Queen+of+Norway+enjoys+art+in+Beijing.htm>

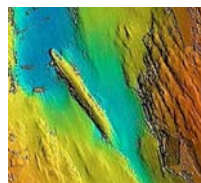


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Kongsberg Multibeam Echosounder



German warship Blücher, Oslofjord



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Synthetic aperture sonar: Hugin



FFI & Kongsberg Maritime

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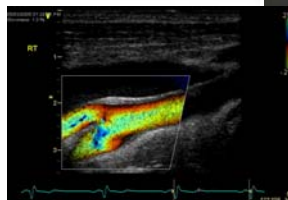
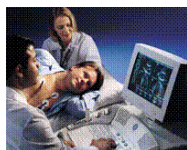


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GE Vingmed Ultrasound



4-chamber cardiac image



Blood flow in the carotid artery
(neck) with bifurcation

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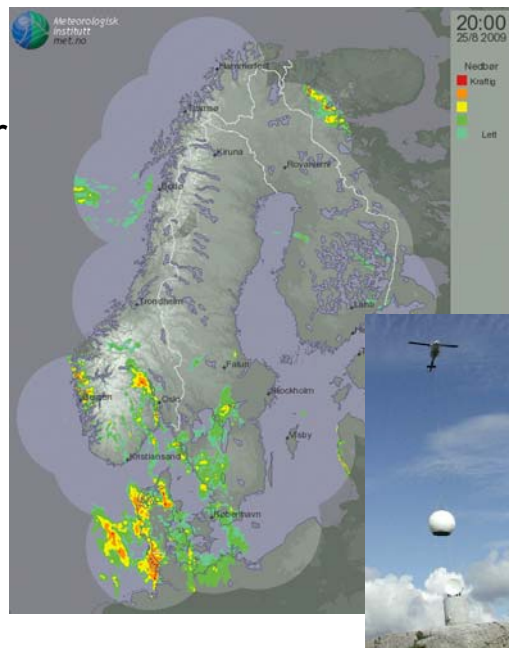
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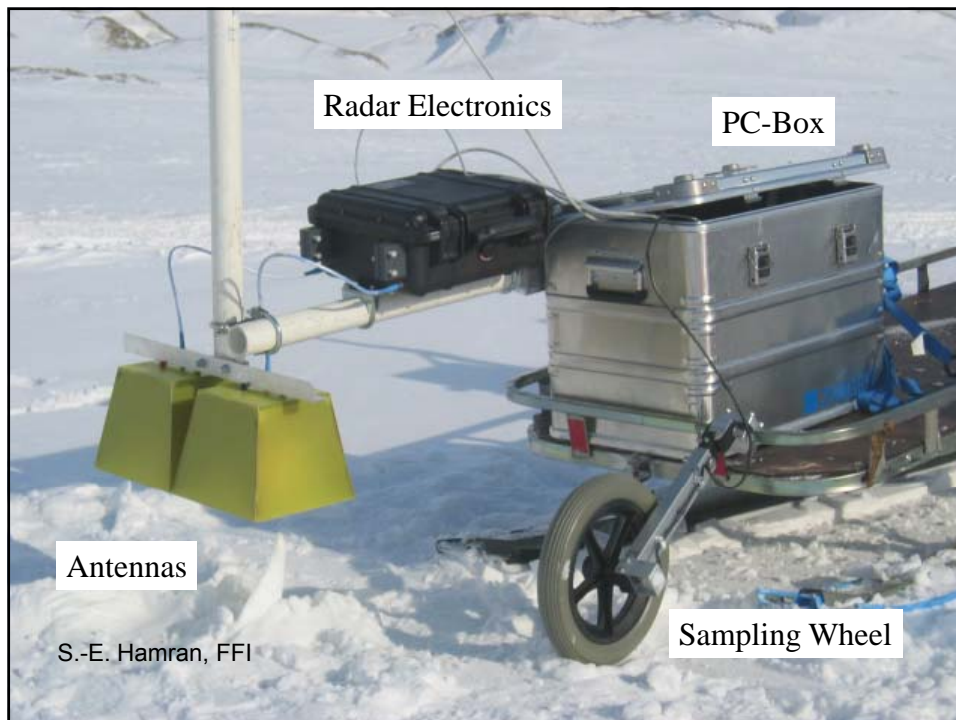
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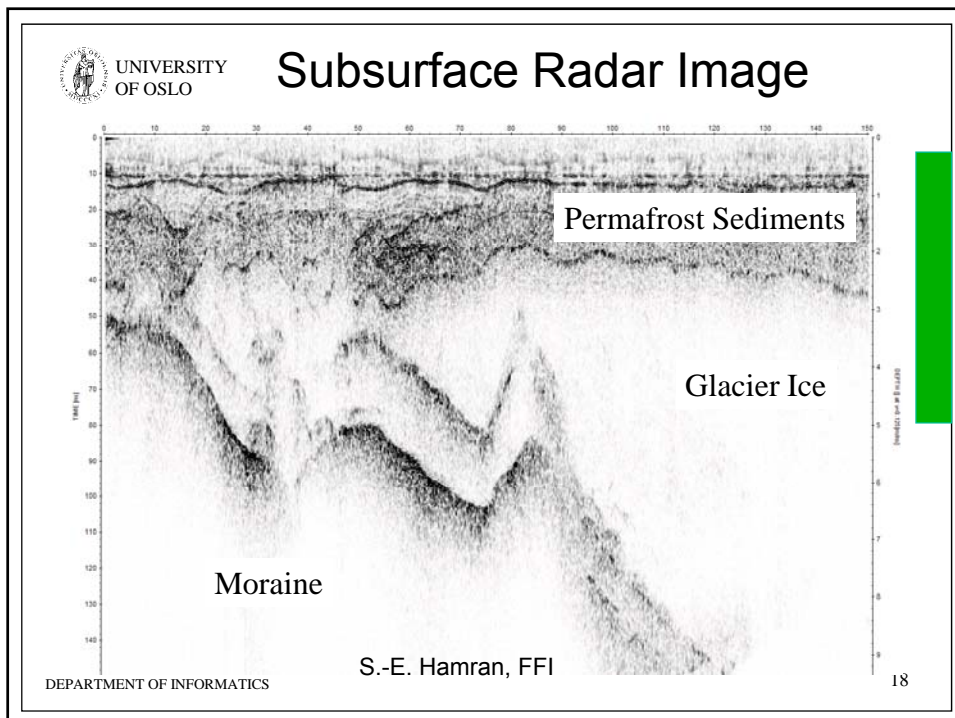
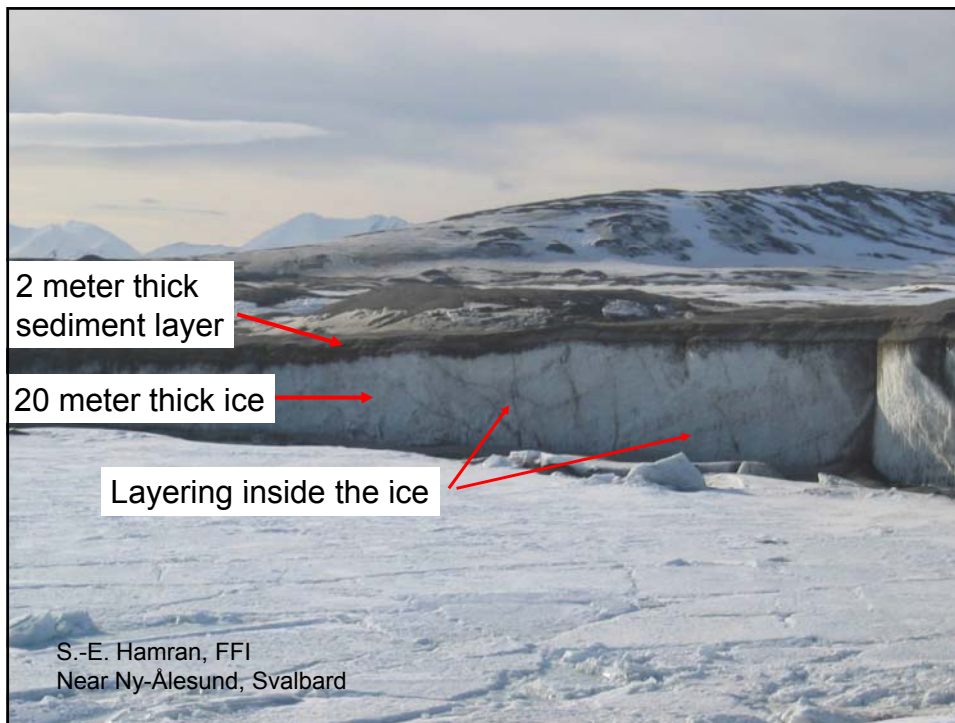
Weather radar

- www.yr.no
- Nordic network
- Both observation of backscatter (rain) and Doppler shift, i.e. wind speed and direction
- Radius of coverage is 240 km.
- Typically: $\lambda=10$ cm, S-band (3 GHz)



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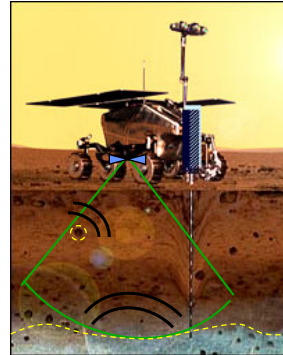




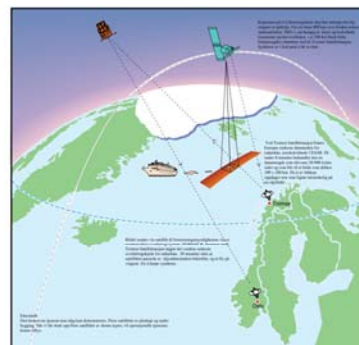
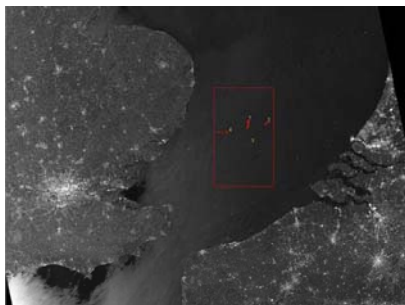


ExoMars Mission

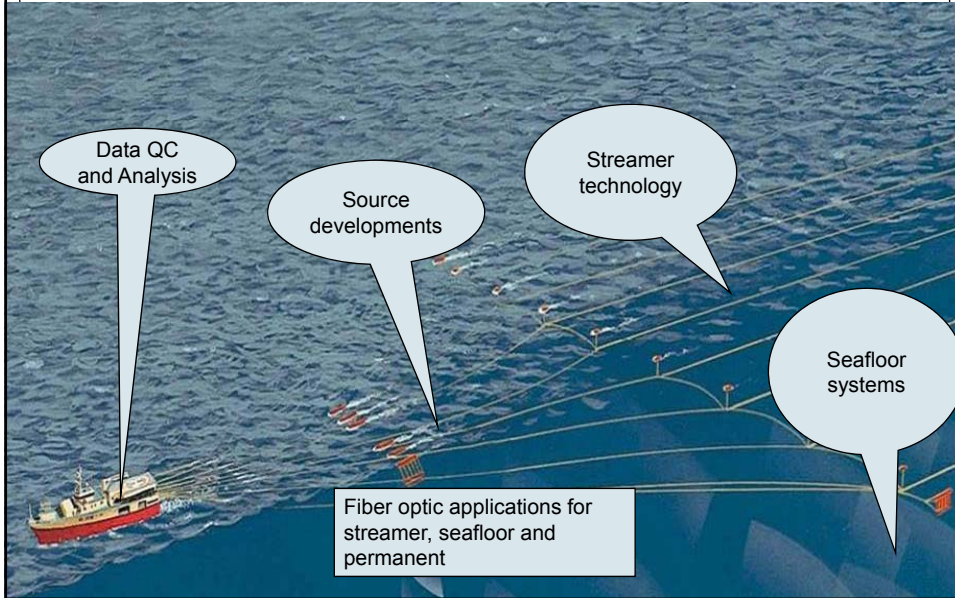
- Scientific objectives:
 - Search for signs of life (past/present) on Mars;
 - To characterise the water/geochemical environment as a function of depth in the shallow subsurface;
 - To study the surface environment and identify hazards to future missions;
 - To investigate the planet's subsurface and deep interior to better understand the evolution and habitability of Mars.
- **Pasteur Rover** with instruments: Camera, Organics detector, Mass spectrometer, GPR, Raman/LIBS, Microscope, Drill.
- **GEP**: Met-sensors, Dust, GPR, Electric field
- **WISDOM** = Water Ice and Subsurface Deposit Observations on Mars



Remote sensing - satellite

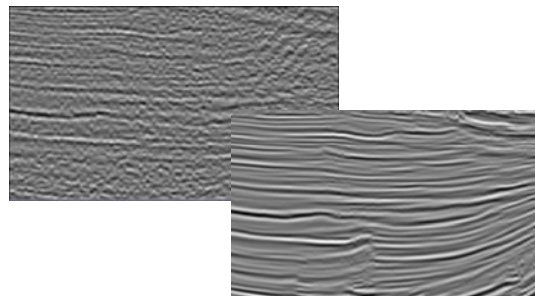


ENVISAT 16. april 2007 at 2333 Norw. time
Four oil spills in the English channel
Copyright: KSAT (Norw. Space Centre)



Seismics

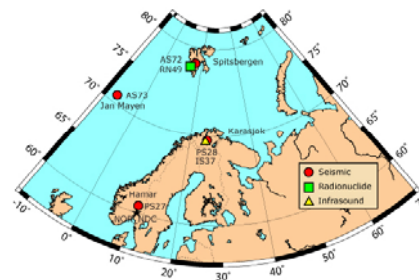
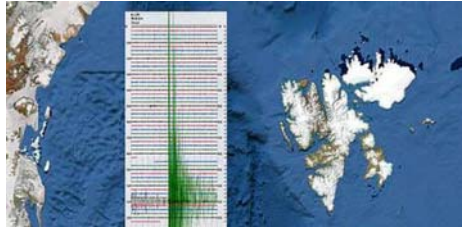
- Improved prestack depth migration
- Data from North Sea





Seismology

- March 2009: An earthquake of magnitude 6.5 outside Svalbard.
- The strongest ever measured in our part of the world
 - <http://www.aftenposten.no/nyheter/iriks/article2964253.ece>
- Norway: 6 stations (out of 50) in the International Monitoring System (IMS)
 - <http://www.norsar.no/c-71-Station-Network.aspx>



2. september 2010



Centre of Imaging

- Established Jan 2006
- Department of Informatics
 - Digital signal processing and image analysis (DSB)
- Department of Geosciences



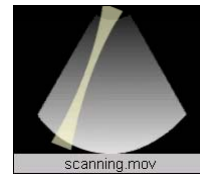
Imaging principles

- **Passive:**
 - Reflection
 - » Optics, remote sensing
 - Direct path (one-way):
 - » Passive sonar
 - » Seismology
 - Tomography:
 - » Seismology
- **Active (with transmitter):**
 - Pulse echo:
 - » Active sonar, medical ultrasound, seismics, radar
 - Controlled emission:
 - » X-ray, MR, PET
 - Tomography:
 - » CT, ultrasound



Echo imaging

- Radar
- Sonar
- Medical Ultrasound
- Non-destructive testing
- Send a 'ping'

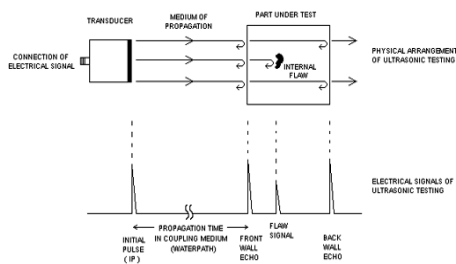


Radial resolution in echo systems

- Radar, sonar, ultrasound
- Resolution = half the pulse length:

$$\Delta r = c\tau / 2 = c / (2\Delta f)$$

- Also inverse proportional to bandwidth, i.e. usually proportional to centre frequency





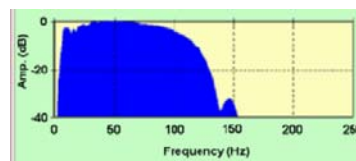
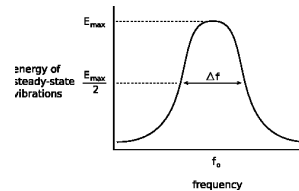
Bandwidth

- Narrowband (relative bandwidth < 10% of center frequency):
 - Optics, remote sensing
 - Radar
 - Sonar (older systems)
 - X-ray
- Wideband:
 - Medical ultrasound
 - Modern sonar
 - Seismics
 - Seismology
- Ultra Wideband (radio)
 - FCC and ITU-R definitions: emitted signal bandwidth exceeds the lesser of 500 MHz or 20% of the center frequency.
 - Frequencies 3.1–10.6 GHz



Radial, axial, vertical resolution for echo systems (along beam)

- Pulsed continuous wave (PW): $c\tau/2$
- Broadband pulse: $c/2\Delta f$, since $\tau=1/\Delta f$
- In many systems the transducer/source is the factor which limits bandwidth:
 - $\Delta f = k f_0 \Rightarrow$ where $k = 50-200\%$ = relative bandwidth
 - If $\Delta f \Leftrightarrow -3\text{dB}$ points, then $1/k = f_0/\Delta f = Q$ -factor
- Radial resolution $c/2\Delta f = c/2k f_0 = Qc/2f_0$
 - inverse proportional to center frequency
 - Ex1 (upper fig): $Q=2$ ($k=0.5$)
 \Rightarrow radial res. = $c/f_0 = \lambda$: **typical for medical ultrasound, e.g. $f_0 = 3.5$ MHz**
 - Ex2 (lower fig): $Q=0.5$ ($k=2$: bandwidth from ~ 0 to $2f_0$) \Rightarrow radial res. = $\lambda/4$: **seismics**





Lateral, horizontal resolution (across beam) for focused beam

- Angular resolution, farfield, focused: $\theta = k \cdot \lambda / d$
 - Definitions: peak-zero, zero-zero, -3dB, -6 dB
 - Constant k depends on aperture (circular, rectangular):
 - » Circular:
 - -3dB: $k=1.02$; peak-zero: $k=1.22$; -6dB: $k=1.41$
 - » Rectangular:
 - -3dB: $k=0.89$; peak-zero: $k=1.0$; -6dB: $k=1.21$
 - Rule-of-thumb: as k is close to 1: $\theta \approx \lambda / d$
- $\lambda = c/f \Rightarrow \theta \approx \lambda / d = c / d \cdot f$:
 - lateral resolution improves (= gets smaller) as the center frequency increases

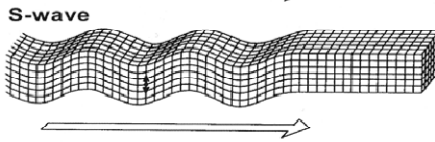
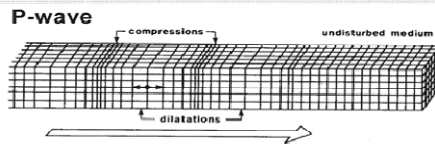


Wave types

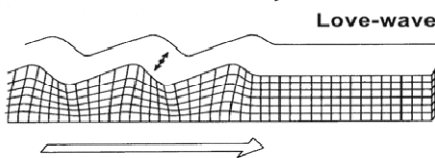
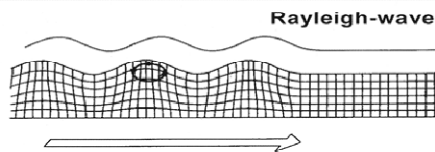
- Electromagnetic waves
 - Optical
 - Infrared, Ultraviolet
 - Radar
 - X-ray (CT – Computer Tomography)
- Mechanical waves
 - Seismics, seismology
 - Audio
 - Ultrasound for sonar and medical ultrasound



WAVE PROPAGATION



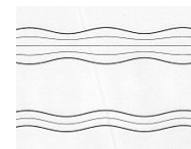
surface waves



Wave types

- Longitudinal: pressure wave (P)
 - Acoustics (mechanical wave) in gases and liquids (audio, sonar, medical ultrasound)
 - Mechanical wave in solids (seismics, seismology)
- Transversal: electromagnetic, shear wave (S)
 - Mechanical wave in solids (seismics, seismology)
 - Also a slowly moving shear wave in medical ultrasound
 - Electromagnetic = optics, IR, X-ray, radar
 - polarization
- Surface waves
 - Rayleigh (vertical): ocean waves, seismology
 - Love, component perpendicular to surface (extensional wave), solids only (shear): seismology
- Plate waves
 - Lamb, parallel to plane layer, perpendicular to wave direction (extensional and flexural)
- Modes of Sound Wave Propagation:

<http://www.ndt-ed.org/EducationResources/CommunityCollege/Ultrasonics/Physics/modepropagation.htm>



Extensional mode with $d / \lambda = 0.6$.
Flexural mode with $d / \lambda = 0.3$.



Snell's law

- $\sin\theta_i/v_i = \sin\theta_t/v_t$
- Single-mode: pressure waves or electromagnetic
- Mixed-mode in solids: mode conversion P \leftrightarrow S
- Optics: index of refraction: $n = v_i/v_t$
- Critical angle: transmitted (refracted) wave is parallel to interface - $\theta_t = 90$ deg
- Non-homogeneous media: $c(x,y,z)$ - varies in space
 - Varies with depth in seismics/seismology: curved waves
 - Varies with depth, salinity, pressure, ... in underwater acoustics

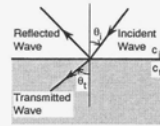
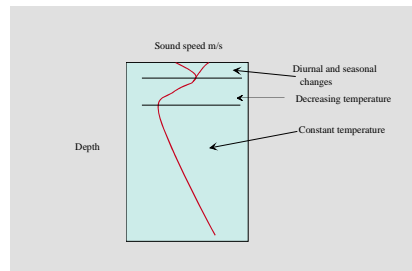
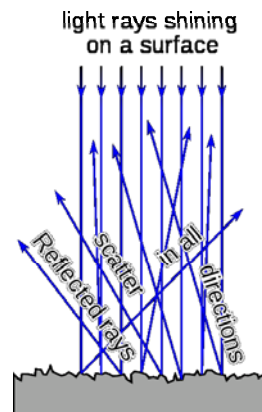


Figure 2.10 An incident wave striking a discontinuity in the medium results in a reflected wave and a transmitted wave. The angle of reflection equals the angle of incidence, and the angle of refraction of the transmitted wave obeys Snell's Law. In this example, the propagation speed in the lower medium is greater than in the upper.



Diffuse – specular reflection

- Diffuse reflection = scattering
 - When surface irregularities are on the order of the wavelength
 - Illustration: Wikipedia
- Specular reflection = mirror
 - When the surface is smooth compared to a wavelength



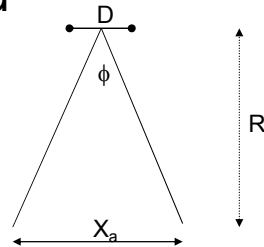


Near field – farfield

- Aperture: D
- Wavelength: $\lambda = c/f$
- Distance to target: R

Independent of type of wave:

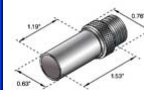
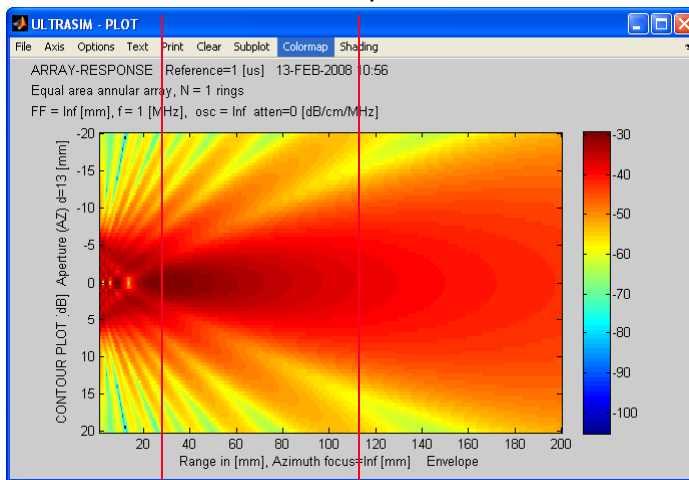
- Angular resolution: $\phi \approx \lambda/D$
- Resolution at target (azimuth): $X_a \approx R \cdot \phi = \lambda \cdot R/D$
- Near field or far field?
If the objective is to distinguish something which is smaller than the aperture, i.e. $X_a < D$, then it is in the near field and focusing is required



- $X_a = D \Leftrightarrow \lambda \cdot R_{nf}/D = D \Leftrightarrow R_{nf} = D^2/\lambda$
- Nearfield-farfield limit: $D^2/4\lambda \dots D^2/\lambda$ (not a hard limit)



1 MHz $D=13$ mm, unfocused xdcr



Olympus-Panametrics A303S (in our lab)

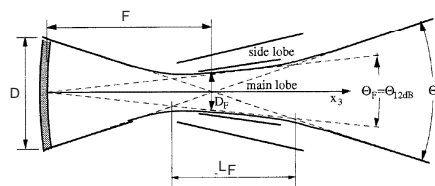
$D^2/4\lambda$

$D^2/\lambda=113$ mm



Near field – farfield

- Near/far field limit: $D^2/4\lambda \dots D^2/\lambda$
- Equivalent to hyperfocal distance in optics
 - nearest focus distance at which the far limit of the depth of field, L_F , extends to infinity
 - i.e. the farthest point to which there is any meaning to focus



Laser pointer

- Aperture: $D = 1\text{mm}(?)$, could be 2
- Wavelength (red): $\lambda = 650\text{ nm}$
- Near/far-transition:
 - $D^2/4\lambda = (1\text{e-}3)^2/650\text{e-}9 \approx 1.5\text{ m}$
 - $D^2/\lambda \approx 6\text{ m}$





Nearfield/farfield

- Farfield: remote sensing, radar, sonar
- Important applications in the near field, i.e. Using focusing:
 - Optics
 - Medical ultrasound
 - Seismics
 - Synthetic aperture radar and sonar
- Extreme nearfield: X-ray (CT), laser
 - Collimated beams
 - One reason why ultrasound tomography (nearfield) is so hard compared to X-ray tomography (extreme nearfield)



Time resolution

- In all pulse-echo systems
- Especially important in medical imaging
 - Pulse Repetition Frequency (PRF) and frame rate must be fast enough to sample the movements of organs in the body
- Also in sonar, radar, seismics



Medical imaging

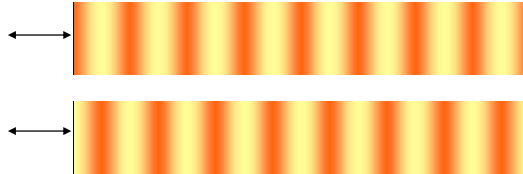
- Ultrasound is best for:
 - Soft tissues, dynamics of blood flow
 - Fetal, cardiac, liver, kidneys, circulatory system
 - Avoid bone and air (lungs)
- CT is best for:
 - Distinguish soft tissue and bone, or tissue and contrast agent
 - Angiography, colon
- MR is best for:
 - Detects magnetic dipole of H₂O molecules
 - Contrast agents, no accumulation of dose as CT
 - Soft tissue: cancer, blood flow (functional MRI)
- SPECT/PET is best for:
 - Based on injection of radioactive isotope
 - Brain activity, cancer (large blood flow)





Wavelength

- The distance travelled by a wave during one period
- A period: $T=1/f$, where f = frequency [Hz]
- Travelled distance: $\lambda = Tc = c/f$



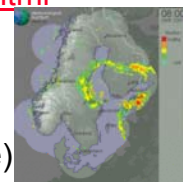
- Shown here: Pressure wave = longitudinal wave
- Transversal waves: electro magnetic waves (optics, radio, ...)
- Other kinds of waves:
 - Shear waves = acoustic waves in solids (e.g. seismics)
 - Surface waves: ocean waves

Figure: J Hovem, TTT4175
Marine acoustics, NTNU



Wavelength, electromagnetic waves

- Speed of light: $c=300,000 \text{ km/sec} = 3 \cdot 10^8 \text{ m/s}$
- Wavelength: $\lambda = c/f$
- Weather radar <http://met.no/radar/sorost.html>
 - S-band frequencies (2.7 to 3 GHz)
 - $\lambda=3e8/3e9 = 10 \text{ cm}$
- Blue-green light (optical sensor in satellite)
 - $\lambda=500 \text{ nm}$
 - $f = c/\lambda = 3e8/500e-9 = 600 \text{ e}12 = 600 \text{ THz}$



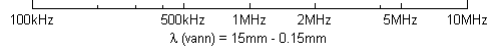


Wavelength, acoustic waves

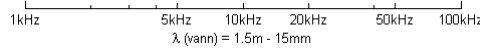
- Speed of sound in ~water: $c=1500$ m/s
- Wavelength: $\lambda = c/f$
- Echo sounder for recreational fish-finding
 - $f = 200$ kHz
 - $\lambda=1500/200e3 = 7.5$ mm
- Medical ultrasound scanner
 - $f = 3$ MHz
 - $\lambda=1500/3e6 = 0.5$ mm
- Seismics
 - $f \sim 50$ Hz
 - $\lambda=1500/50 = 30$ m (in water, not in sediment)



Sonars - Non-destructive testing, medical

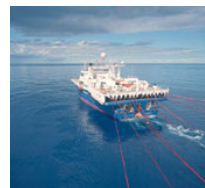
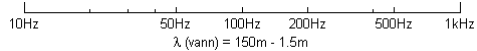


Sonars, echosounders



Geophysical

Geophysics: shallow seismic



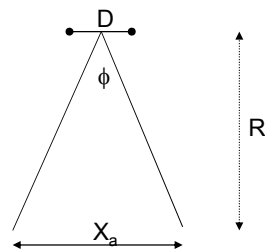


Resolution

- Aperture: D
- Wavelength: $\lambda = c/f$
- Distance to target: R

Independent of type of wave:

- Angular resolution: $\phi \approx \lambda/D$
- Resolution at target (azimuth):
 $X_a \approx R \cdot \phi = \lambda \cdot R/D$
- Near field or far field?
If the objective is to distinguish something which is smaller than the aperture, i.e. $X_a < D$, then it is in the near field and focusing is required



- NB! Resolution must always be considered in relation to wave length
- Regardless of whether the wave is acoustic, seismic, electromagnetic, optical, ...



Satellite: optics, IR, radar

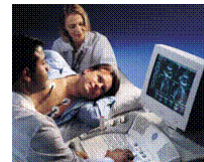
- Polar orbit, height: $R=800$ km

Sensor	Wave length	Aperture	Ground resolution	Near field?
Light blue-green	$\lambda=500$ nm	$D=40$ mm	$X_a = \lambda \cdot R/D = 0.5 \cdot 10^{-6} \cdot 800 \cdot 10^3 / 0.04 = 10$ m	$X_a > D$: far field
Thermal IR	$\lambda=10$ μ m	$D=80$ cm	$X_a = \lambda \cdot R/D = 10 \cdot 10^{-6} \cdot 800 \cdot 10^3 / 0.8 = 10$ m	$X_a > D$: far field
Radar	$f=3$ GHz, $\lambda=10$ cm	$D=10$ m	$X_a = \lambda \cdot R/D = 0.1 \cdot 800 \cdot 10^3 / 10 = 8$ km	$X_a > D$: far field
Radar, synthetic aperture		$D=8$ km	$X_a = \lambda \cdot R/D = 0.1 \cdot 800 \cdot 10^3 / 8 \cdot 10^3 = 10$ m	$X_a < D$: near field



Medical ultrasound

- Cardiology:
 - Aperture $D = 19$ mm, Depth $R = 50$ mm,
 - $f = 3.5$ MHz $\Rightarrow \lambda = 1540/3.5 \cdot 10^6 = 0.44$ mm
- Resolution:
 - $X_a = \lambda \cdot R/D = 0.44 \cdot 50/19 = 1.1$ mm
 - $X_a < D$: near field
- Near field/ far field limit:
 - $X_a = D \Leftrightarrow \lambda \cdot R_{nf}/D = D \Leftrightarrow R_{nf} = D^2/\lambda$
 - Often $D^2/4\lambda$
 - Medical ultrasound: limit $R_{nf} = 19^2/0.44 = 820$ mm = 0.82 m
 - Always operates in the near field and focusing is always required





Sonar

- Sonar:
 - $f = 2.5 - 500$ kHz
 - $D = 8$ m – 10 cm
- Typical:
 - $D = 1$ m, $R = 1$ km
 - $f = 50$ kHz $\Rightarrow \lambda = 1480/50 \cdot 10^3 \approx 3$ cm
- Resolution:
 - $X_a = \lambda \cdot R/D = 3 \cdot 10^{-2} \cdot 1000/1 = 30$ m
 - $X_a > D$: far field
 - $R_{nf} = D^2/\lambda \approx 34$ m
 - Sonars usually operate in the far field except for very high frequencies, i.e. $f >$ approx. 200 kHz



Tx array

Rx array

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Seismics

- Deep seismics:
 - $D = 1$ km (streamer), $R = 2$ km,
 - $f =$ approx. 50 Hz (broad band) $\Rightarrow \lambda = 3000/50 = 60$ m
- Resolution:
 - $X_a = \lambda \cdot R/D = 60 \cdot 2/1 = 120$ m
 - $X_a < D$: near field
 - NB! Inhomogeneous medium, c varies



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Eyes and ears

Eyes:

- $D = 1.5 - 8 \text{ mm}$,
- $R = 1 \text{ m}$
- $\lambda = 400\text{-}700 \text{ nm}$
- Resolution: $X_a = \lambda \cdot R/D = 500 \cdot 10^{-9} \cdot 1000/8 \approx 0.06 \text{ mm}!$
- $X_a < D$: near field; therefore we have an adaptive lens
- Presbyopia: stiffer and less flexible lens with age



Ears:

- Distance: $D = 17.5 \text{ cm}$
 - $f = 1000 \text{ Hz}$
 - $\lambda = 340/1000 = 34 \text{ cm}$
 - Assume $R = 5 \text{ m}$
 - $X_a = \lambda \cdot R/D = 0.34 \cdot 5/0.175 = 9.7 \text{ m}$
- Duplex theory - Rayleigh 1907:
 - IPD Interaural phase difference for $f < \text{approx. } 1.5 \text{ kHz}$
 - ILD Interaural level difference for higher frequencies
 - Head-related transfer function (HRTF) due to shape of outer ear



Why are antennas for mobile phone base stations tall and narrow?





På norsk

- (Angular) resolution = (Vinkel)oppløsning
- Bølgelengde, trykkbølger, skjærbølger, overflatebølger, båndbredde, nærfelt, fjernfelt, (syntetisk) aperture,



Recommended animations

- Acoustics and Vibration Animations
- Dan Russell, Kettering University, Flint, MI
- <http://www.gmi.edu/~drussell/Demos.html>