INF-GEO 4310
Imaging

Introduction

Sverre Holm

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.

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
- Problem solving:
  Wednesday 10:15-12:15
  - 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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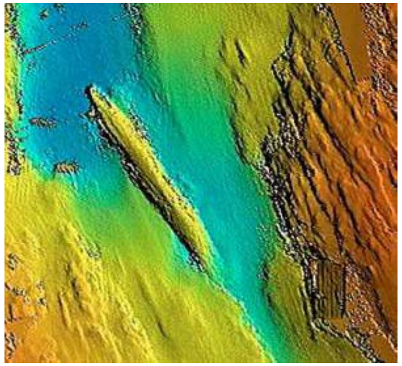
Orion’s Belt

- 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 Albregtsen

- 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 UDs nettside her:
- http://www.norway.cn/culture/Exhibitions/The+Queen+of+Norway+enjoys+art+in+Beijing.htm

Kongsberg Multibeam Echosounder



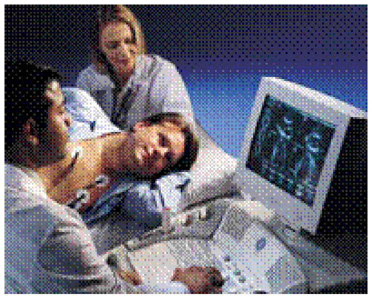
German warship Blücher, Oslofjord

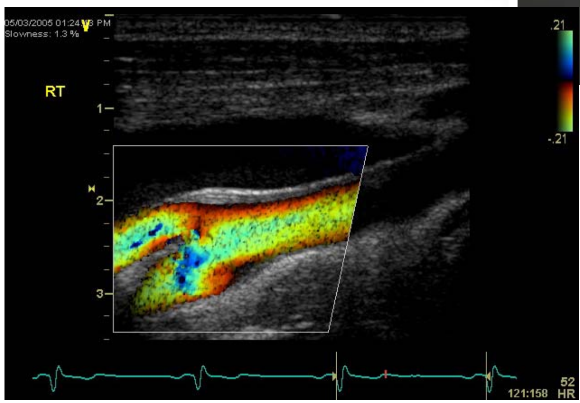
Synthetic aperture sonar: Hugin

FFI & Kongsberg Maritime

GE Vingmed Ultrasound

4-chamber cardiac image

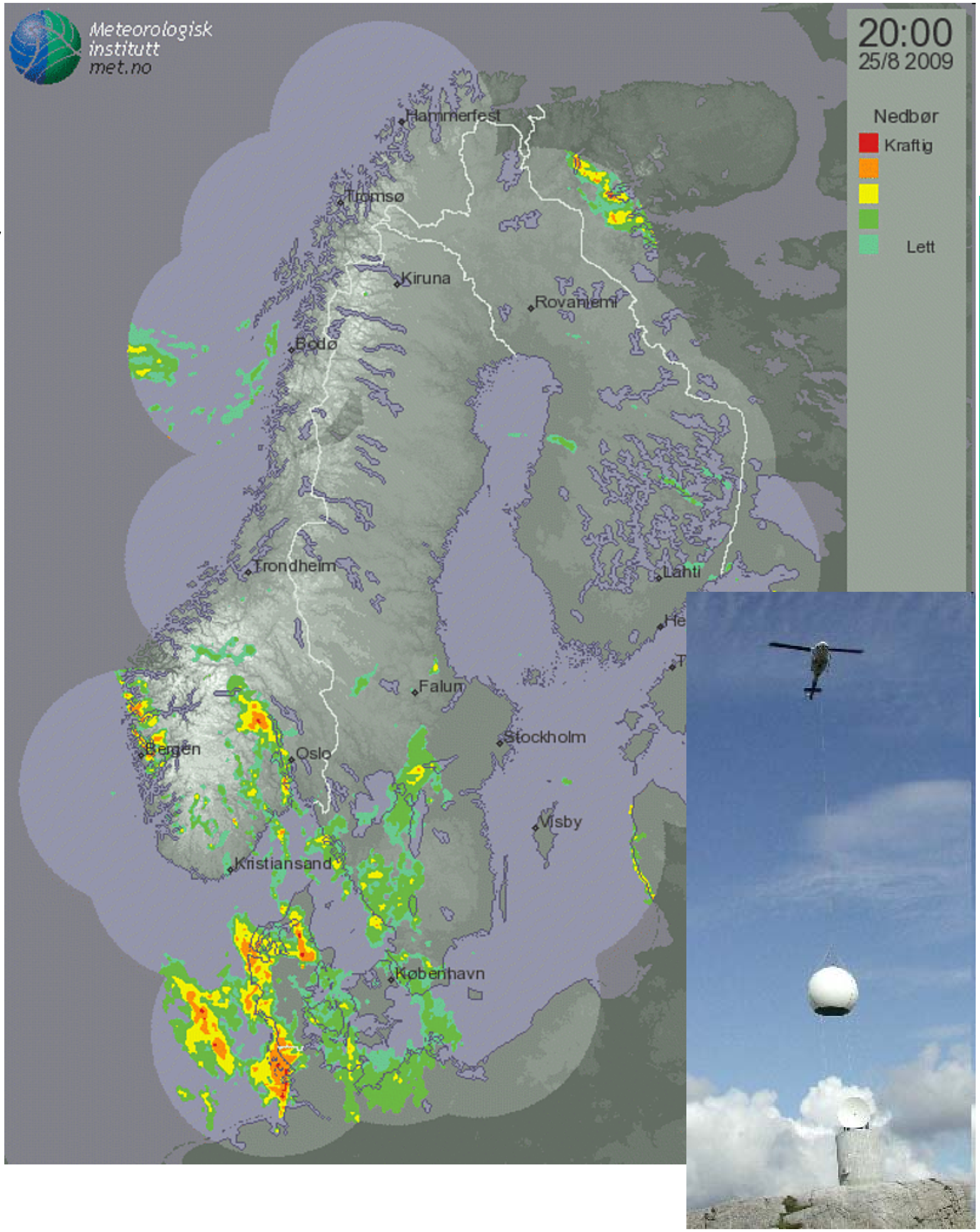


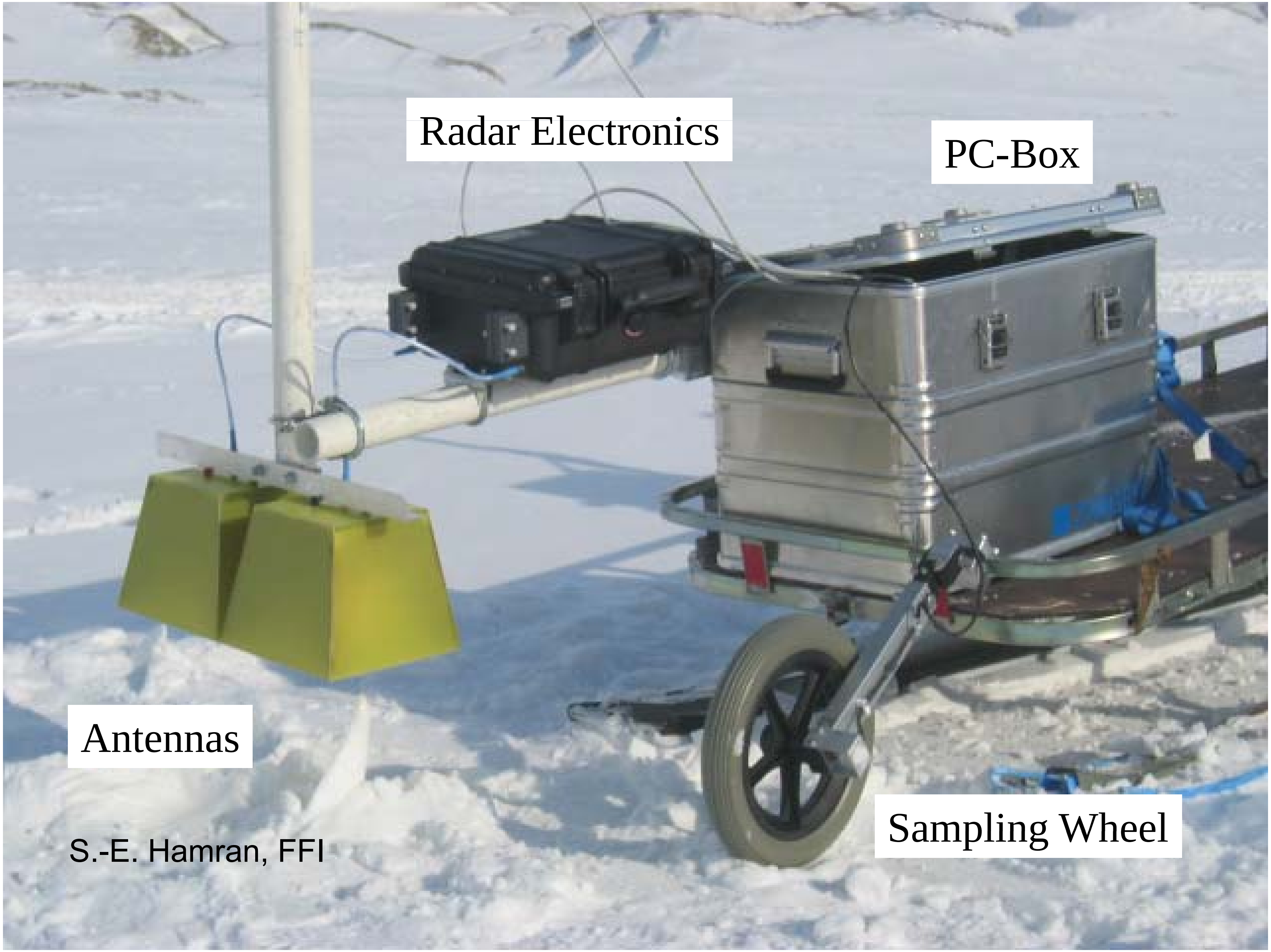


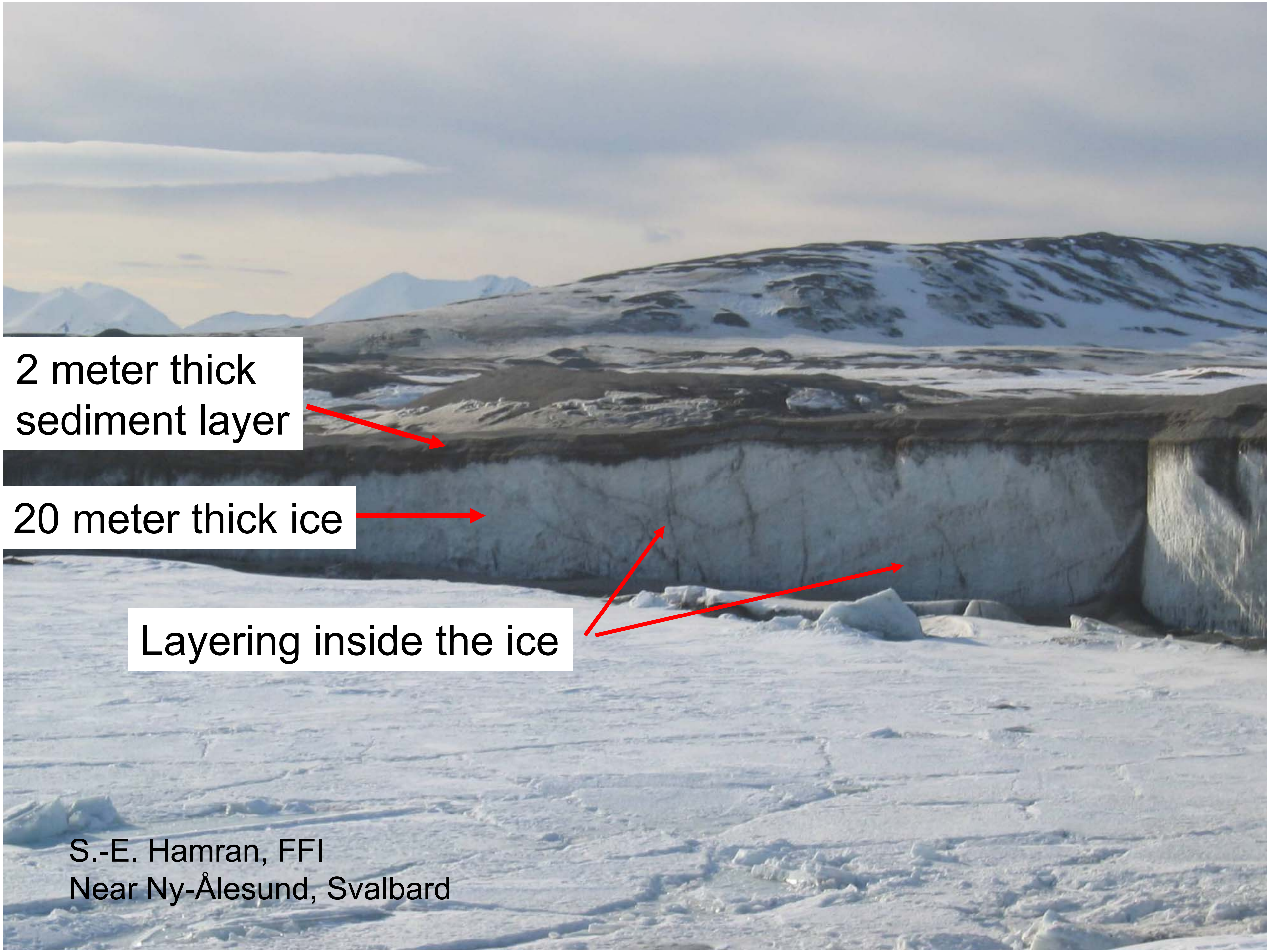
Blood flow in the carotid artery (neck) with bifurcation

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: λ=10 cm, S-band (3 GHz)




Radar Electronics
PC-Box
Antennas
Sampling Wheel
S.-E. Hamran, FFI


2 meter thick
sediment layer
20 meter thick ice
Layering inside the ice
S.-E. Hamran, FFI
Near Ny-Ålesund, Svalbard

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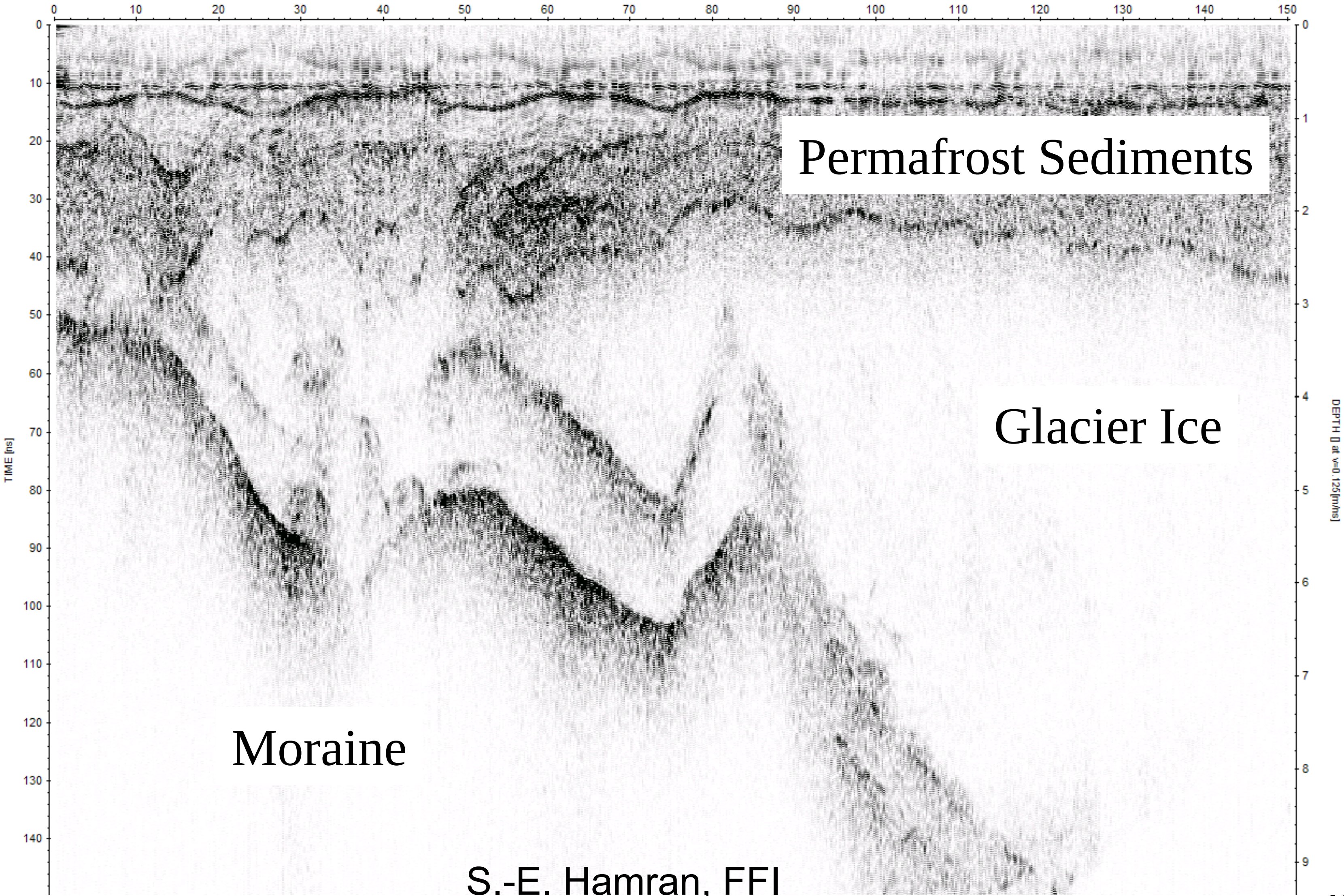
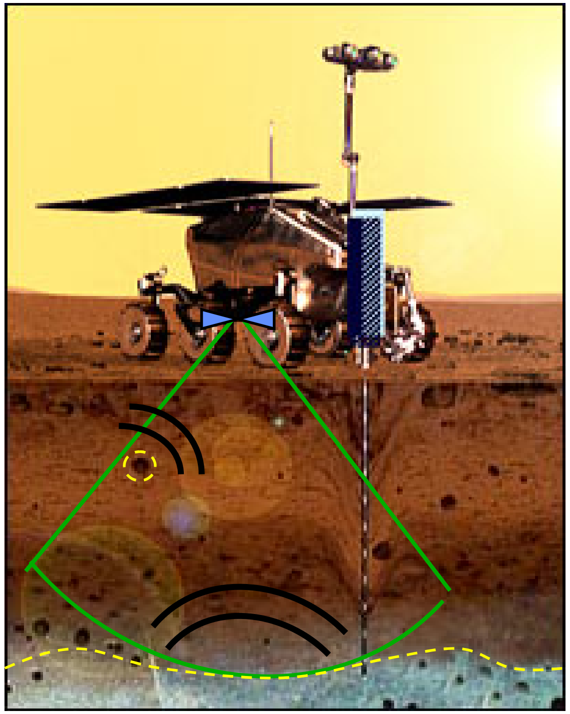
Subsurface Radar Image



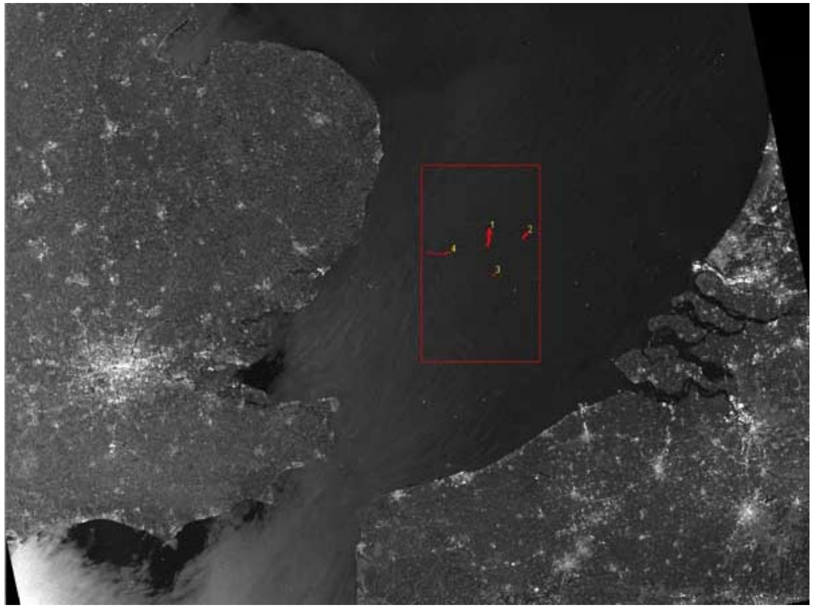
S.-E. Hamran, FFI

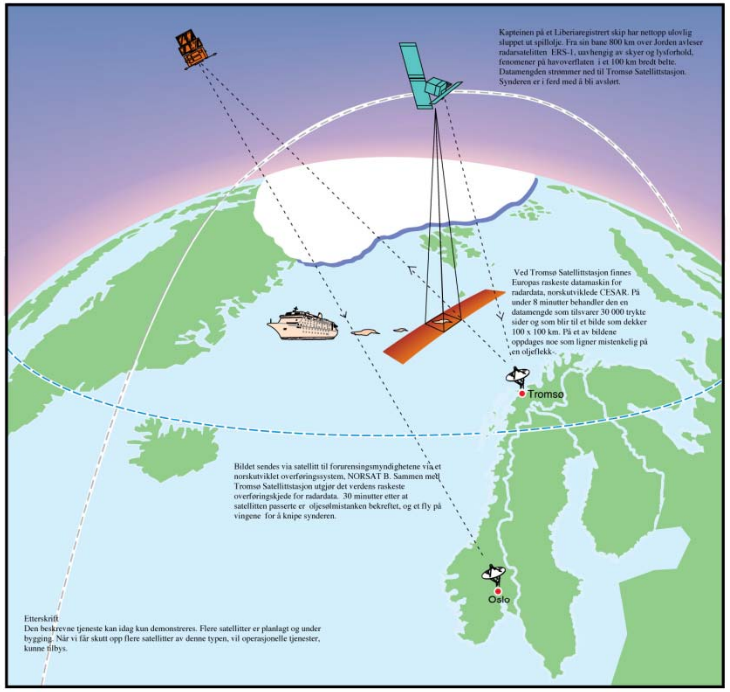
ExoMars Mission



- 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)

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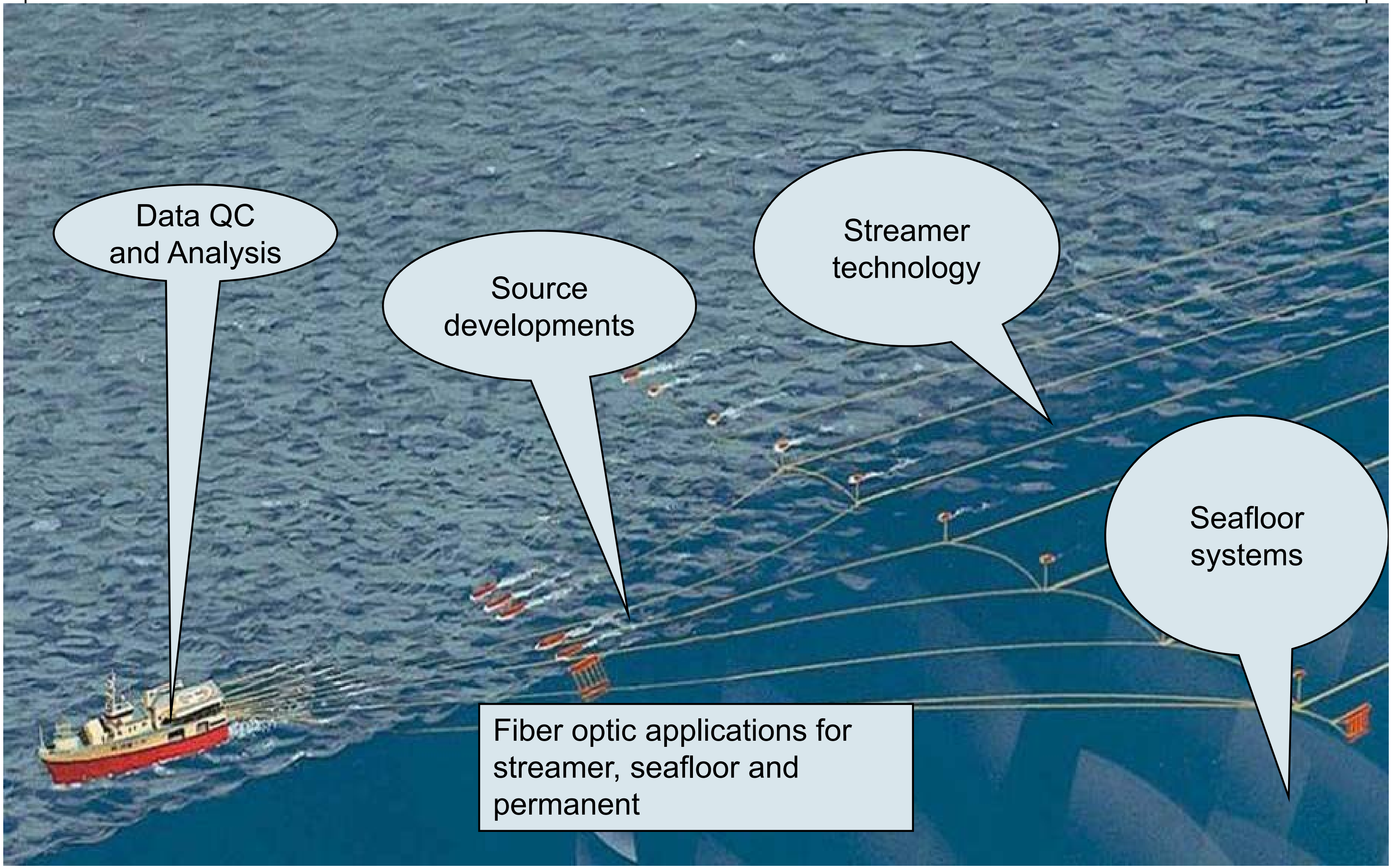
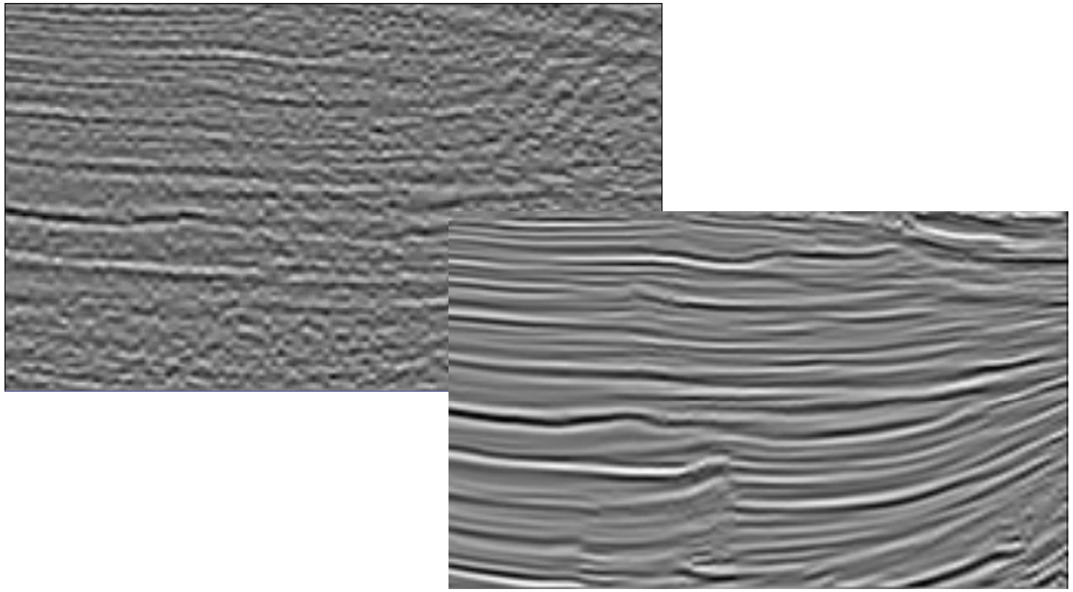


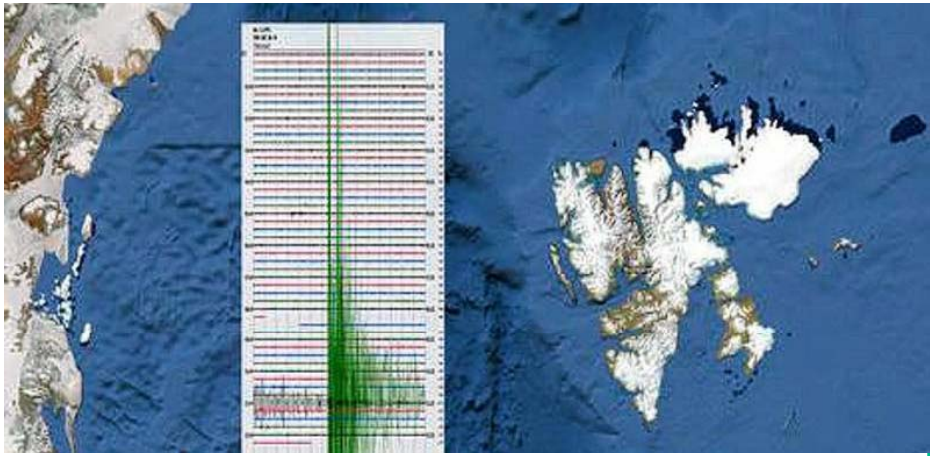
Seismics

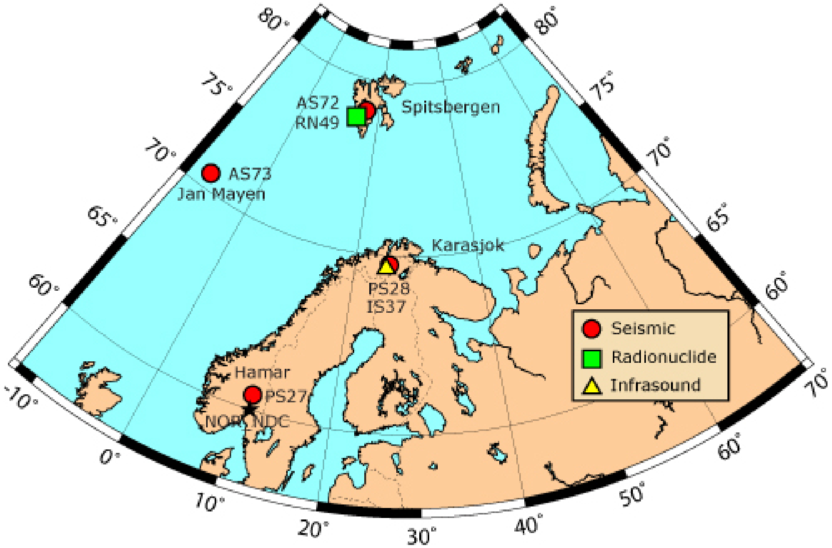
- Improved prestack depth migration
- Data from North Sea



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





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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'

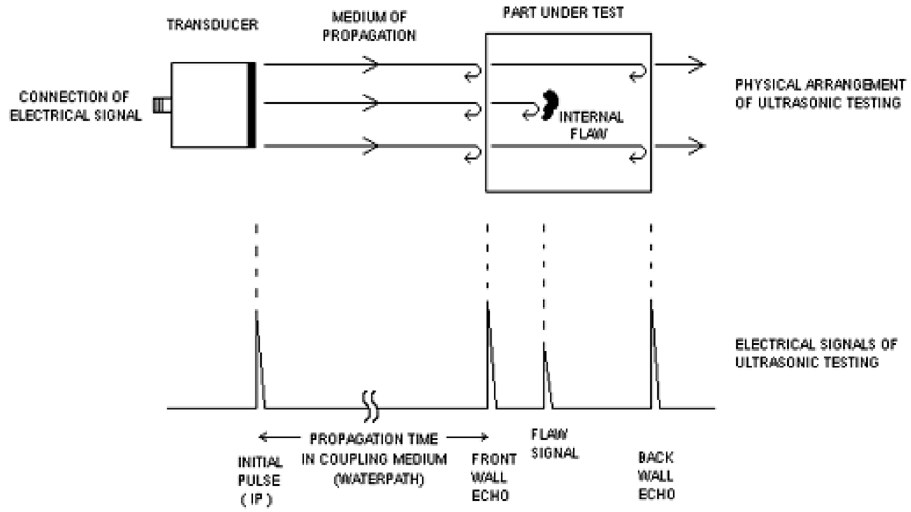
scanning.mov

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

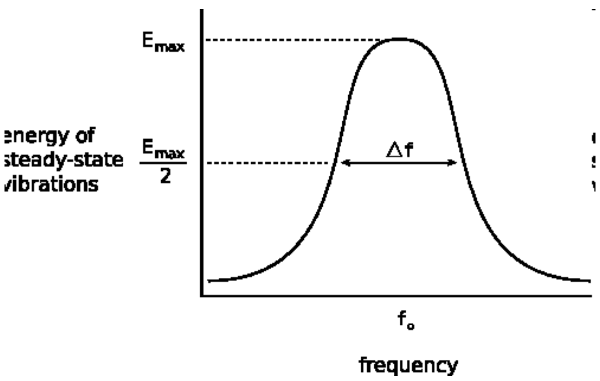


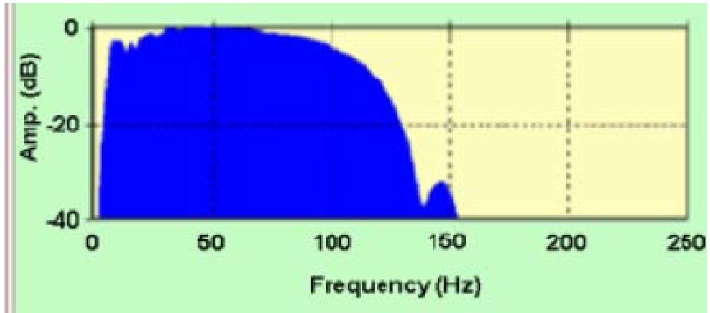
Bandwidth

- 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:
  - $\Delta f = k f_0$ => where k = 50 -200% = relative bandwidth
  - If $\Delta f \Leftrightarrow$ -3dB points, then $1/k = f_0/\Delta f$ = Q-factor
- Radial resolution $c/2\Delta f = c/2kf_0 = Qc/2f_0$ - inverse proportional to center frequency
  - Ex1 (upper fig): Q=2 (k=0.5) => 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 $2f_0$) => 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 to1: $\theta \approx \lambda / d$
- $\lambda = c/f \Rightarrow \theta \approx \lambda / d = c/(d \cdot f)$:
  - 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

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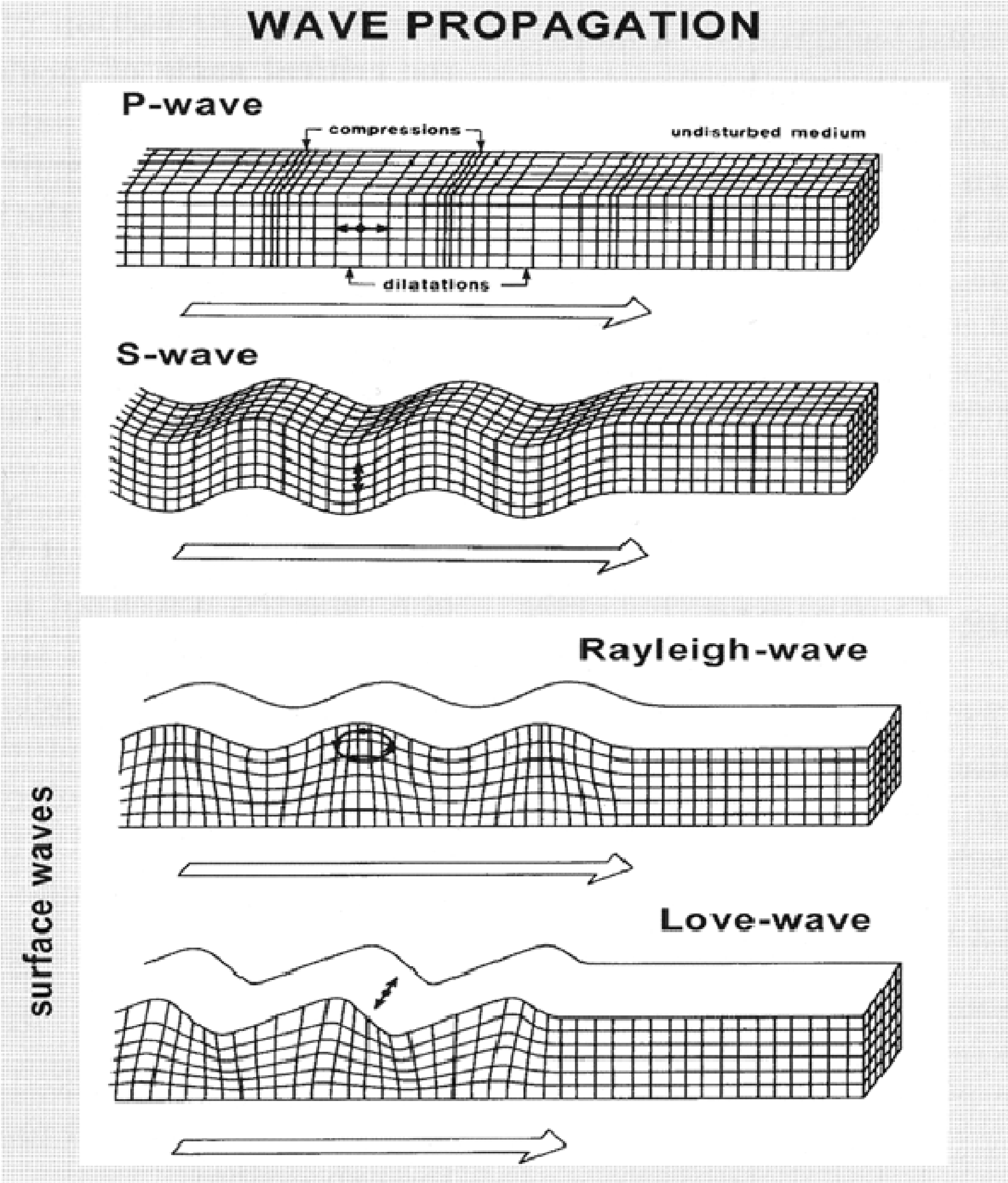
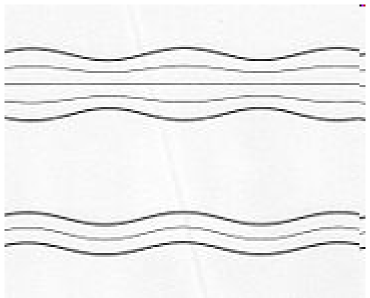


Wave types

- 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 / λ = 0.6.
Flexural mode with d / λ = 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<-> S
- Optics: index of refraction: $n = v_i/v_t$
- Critical angle:transmitted (refracted) wave is parallel to interface - θ_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

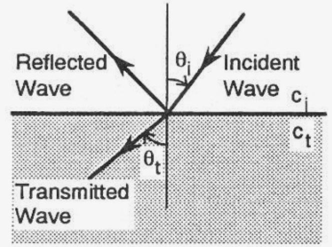
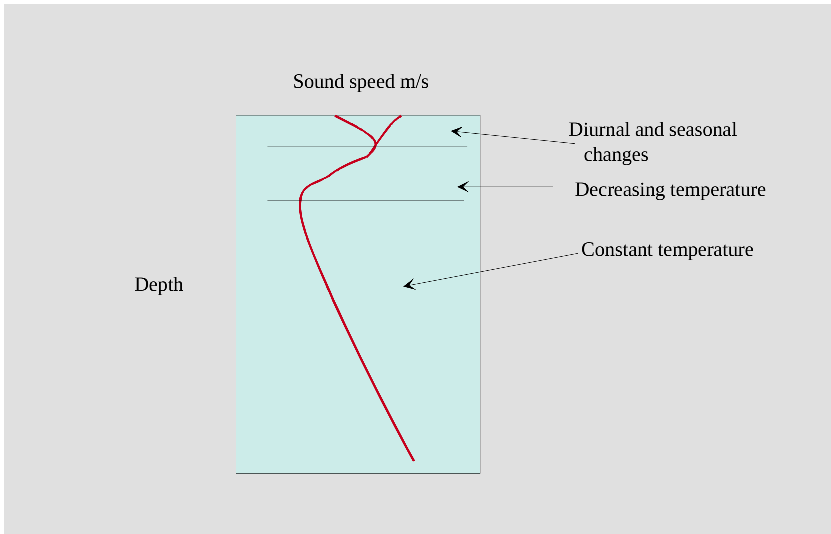
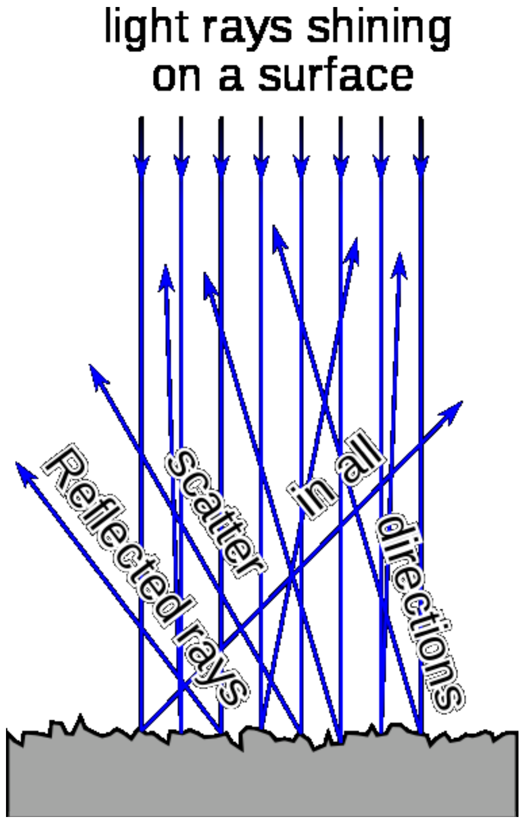


Figure 2.10 An incident wave striking a discontinuity in the medium results in a reflected wave and a transmitted wave. The angle of reflection equals the angle of incidence, and the angle of refraction of the transmitted wave obeys Snell's Law. In this example, the propagation speed in the lower medium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



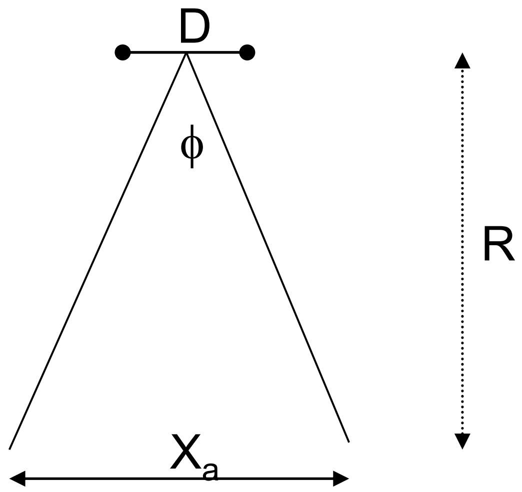
Diffuse – specular reflection

- 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



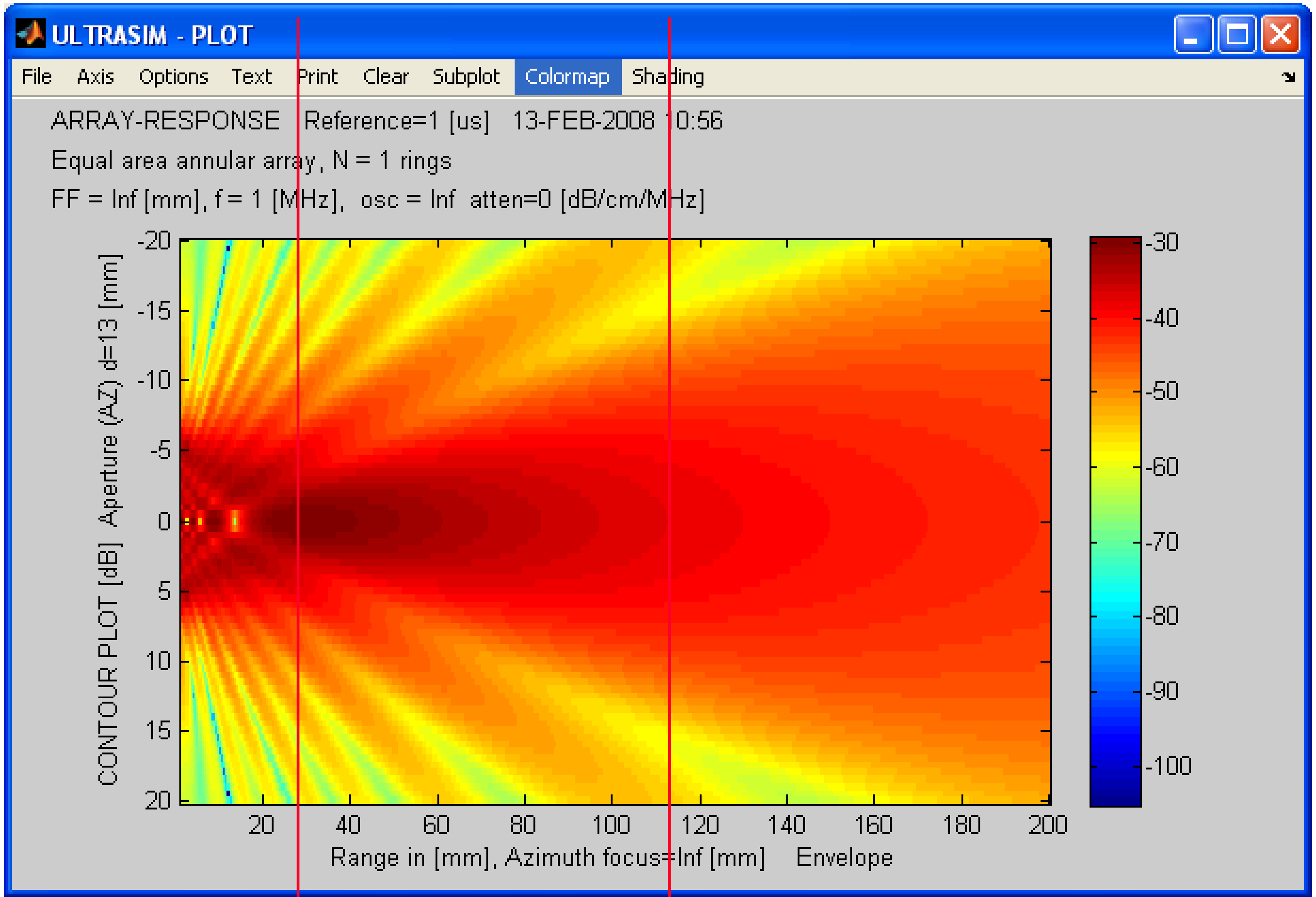
- Aperture: D
- Wavelength: $\lambda = c/f$
- Distance to target: R

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:
  $D^2/4\lambda$ ... D^2/λ (not a hard limit)

1 MHz D=13 mm, unfocused xdcr



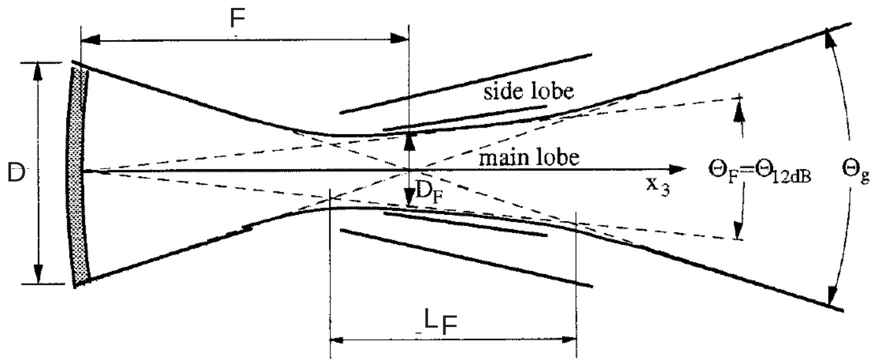
$D^2/4\lambda$

D^2/λ=113 mm

Olympus-Panametrics
A303S
(in our lab)

Near field – farfield

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

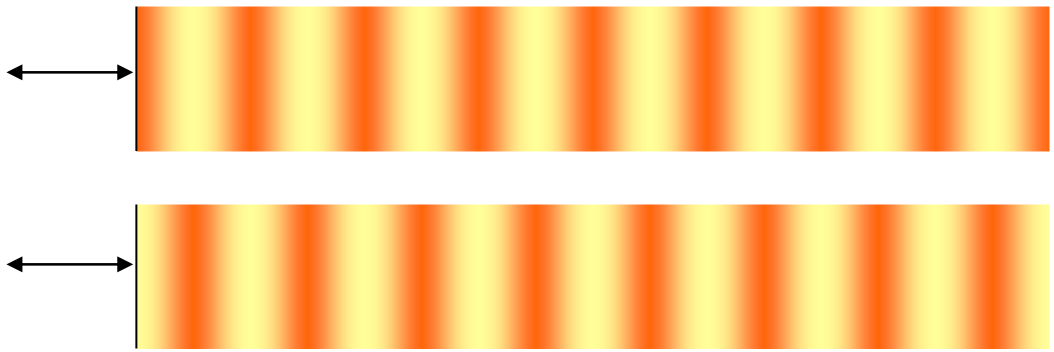
- In all pulse-echo systems
- Especially important in medical imaging
  - Pulse Repetition Frequency (PRF) and frame rate must be fast enough to sample the movements of organs in the body
- Also in sonar, radar, seismics

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 H_2O 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: λ = Tc = c/f

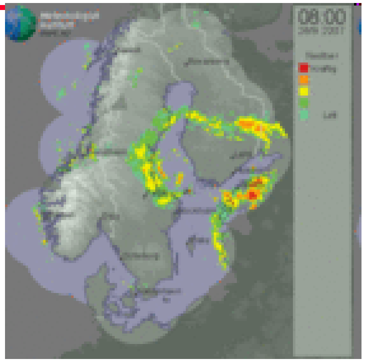


- Shown here: Pressure wave = longitudinal wave
- Transversal waves: electro magnetic waves (optics, radio, ...)
- Other kinds of waves:
  - Shear waves = acoustic waves in solids (e.g. seismics)
  - Surface waves: ocean waves

Figure: J Hovem, TTT4175
Marine acoustics, NTNU

Wavelength, electromagnetic waves

- Speed of light: c=300,000 km/sec = $3 \cdot 10^8$ m/s
- Wavelength: λ = c/f
- Weather radar http://met.no/radar/sorost.html
  - S-band frequencies (2.7 to 3 GHz)
  - λ=3e8/3e9 = 10 cm



- Blue-green light (optical sensor in satellite)
  - λ=500 nm
  - f = c/λ = 3e8/500e-9 = 600 e12 = 600 THz

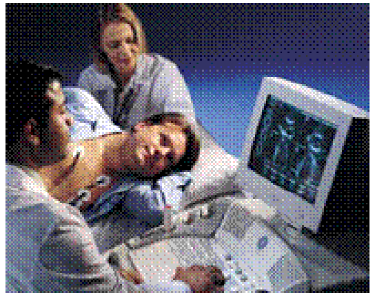
Wavelength, acoustic waves

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

Sonars - Non-destructive testing, medical

100kHz 500kHz 1MHz 2MHz 5MHz 10MHz

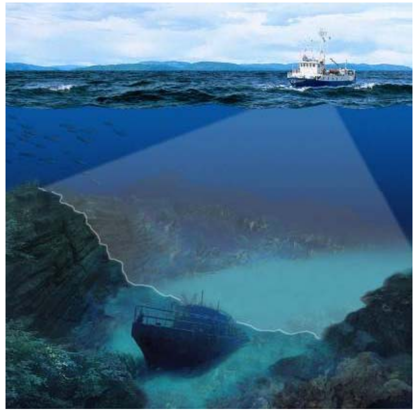
λ (vann) = 15mm - 0.15mm



Sonars, echosounders

1kHz 5kHz 10kHz 20kHz 50kHz 100kHz

λ (vann) = 1.5m - 15mm



Geophysical Geophysics: shallow seismic

10Hz 50Hz 100Hz 200Hz 500Hz 1kHz

λ (vann) = 150m - 1.5m

Resolution

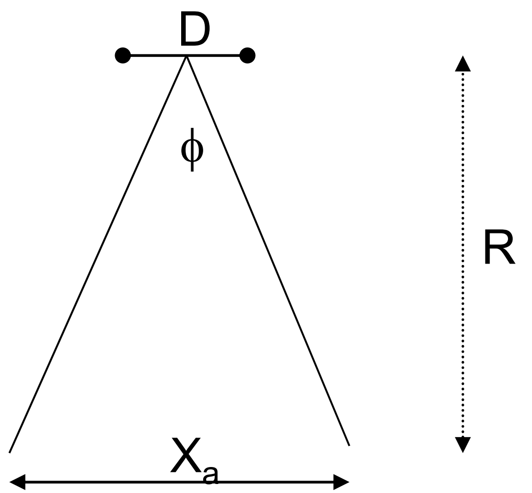
- Aperture: D
- Wavelength: $\lambda = c/f$
- Distance to target: R

Independent of type of wave:

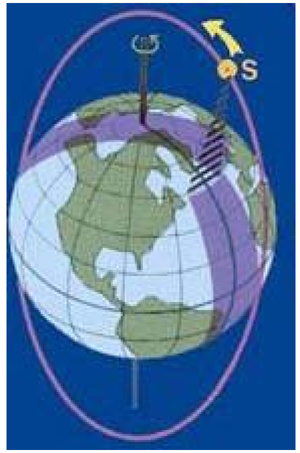
- Angular resolution: $\phi \approx \lambda/D$

- 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, ...



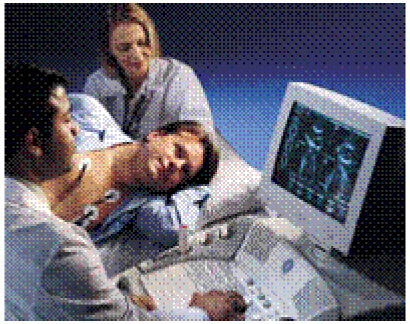
Satellite: optics, IR, radar

- Polar orbit, height: R=800 km

Sensor	Wave length	Aperture	Ground resolution	Near field?
Light blue-green	λ=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	λ=10 μm	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, λ=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 => $\lambda = 1540/3.5 \cdot 10^6 = 0.44$ 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 => $\lambda = 1480/50\cdot10^3 \approx 3$ cm
- Resolution:
  - $X_a = \lambda\cdot R/D = 3\cdot10^{-2} \cdot 1000/1 = 30$ 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

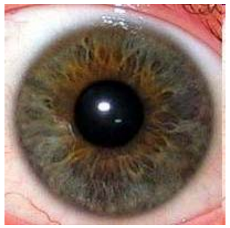
Seismics

- Deep seismics:
  - D = 1 km (streamer), R = 2 km,
  - f = approx. 50 Hz (broad band) => λ = 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

Eyes and ears

Eyes:

- D = 1.5 - 8 mm,
- R = 1 m
- λ = 400-700 nm
- Resolution: $X_a = \lambda \cdot R/D = 500 \cdot 10^{-9} \cdot 1000/8 \approx 0.06$ 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 cm
- f = 1000 Hz
- λ = 340/1000 = 34 cm
- Assume R = 5 m
- $X_a = \lambda \cdot R/D = 0.34 \cdot 5/0.175$ = 9.7 m

- Duplex theory - Rayleigh 1907:
  - IPD Interaural phase difference for f< approx. 1.5 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