INF5410
Signal processing in space and time

Sverre Holm

INF5410 – What will you learn?

The course gives an introduction to spatial signal processing, with emphasis on the differences compared to time domain signal processing.

The course will also give an understanding of basic terminology in acoustics and electro magnetics required to master theory and realization of imaging systems based on signal processing.

INF5410 builds on

- INF3470 – Signal Processing
- STK1100 – Probability and statistical modeling
- MAT1120 - Linear algebra

Estimation Theory

- Needed for chapter 7
- If you lack a background in it, follow lectures in INF 4480 Signal Processing II
  - Stochastic Processes
  - Estimation Theory

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Signal processing in space and time

- Home page: INF5410
  - Wednesday 12.15-14.00:
  - Thursday 13.15-15.00
    - » The two-three first hours will be used for new material
    - » The last hour will be used for problem solving
  - Curriculum
  - Plan
  - Lecturers
- Home page, IFI: INF5410
  - History back to the start in 1993

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PhD course INF9410

- Extra curriculum: 4-5 papers from our research
- Mandatory exercises: all problems, even voluntary ones, must be answered

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Applications

- Underwater Acoustics
- Medical Ultrasound
- Seismics
- Audio
- Radar
- Radio Astronomy

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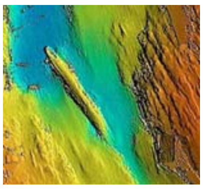
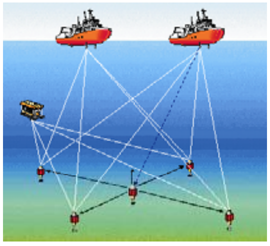
Kongsberg Multibeam Echosounder

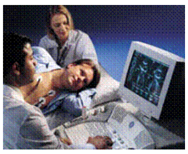


Blücher

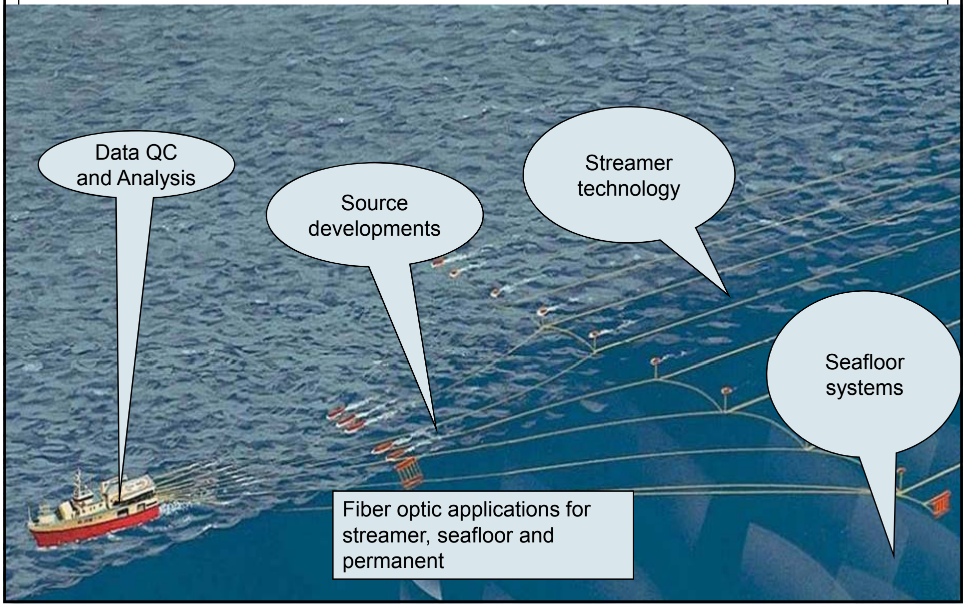
Kongsberg Maritime: Hydroacoustic positioning reference - HPR



GE Vingmed Ultrasound

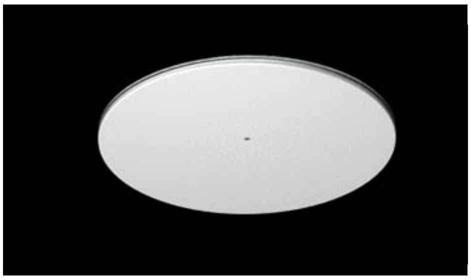


PGS



Squarehead Technology, Oslo

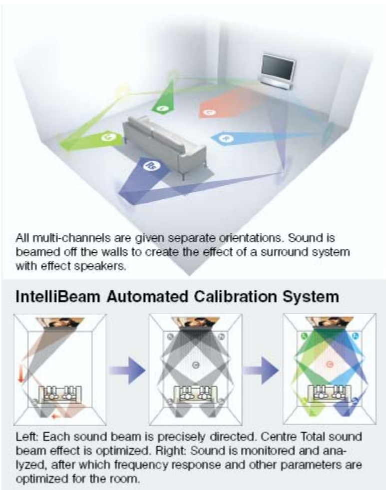
Squarehead Technology, Oslo



Microphone Array

- 300 microphones
- 2.2 meters
- 36 kg
- Wide angle camera

Digital sound projector



- Yamaha YSP-1000
- 42 separate digital power amplifiers, driving 40 ‘sound beam’ drivers and two woofers

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Constructive or destructive interference?

- The PA system, assembled for Iron Maiden, represented state-of-the-art technology in the late 70s
- It consists of folded horn bass, horn loaded midrange and bi-radial horn high frequency elements thrown into a big pile. What it lacked in sonic uniformity it made up for in sound pressure level; which was pretty impressive.
- Nobody apart from a few heavy duty math freaks had heard of interference effect or line (source) arrays at that time.

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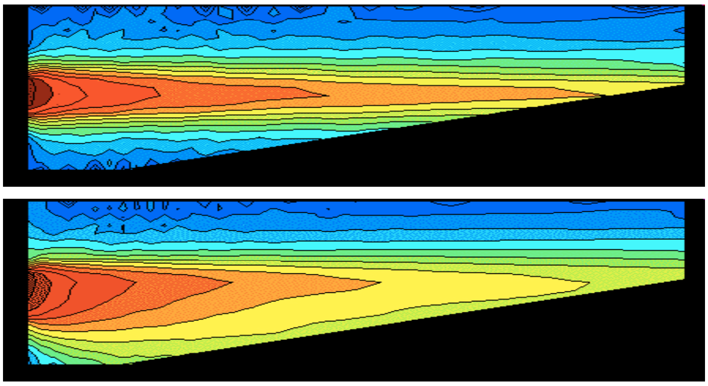
J-arrays: Physically smaller compared to the stack of the 70/80s

Un-shaded straight vertical line array vs J-shaped array



Can produce reasonably even front to rear SPL (volume) using "Angular Shading" or "Amplitude Shading."

http://www.gtaust.com/filter/

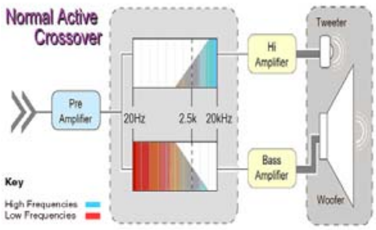
Beaming in 2-/3-way loudspeakers

Goal: absence of sudden change in directivity with frequency.

- Crossover filter must:
  1. Sum to unity gain
  2. Ensure same phase for the two drivers in crossover region

The only crossover filter that satisfies this is the Linkwitz-Riley crossover filter:

- same delay for each loudspeaker



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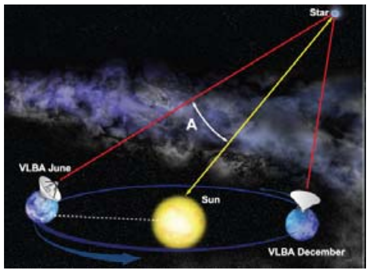
Very Long Baseline Array

Observatories that have taken part in VLBI observations.



http://www.merlin.ac.uk/about/layman/vlbi.html
http://www.nrao.edu/pr/2008/vlbiastrometry/

Very Long Baseline Interferometry provides extremely high precision that can extend use of the parallax technique to many more celestial objects. Parallax is a direct means of measuring cosmic distances by detecting the slight shift in an object's apparent position in the sky caused by Earth's orbital motion.

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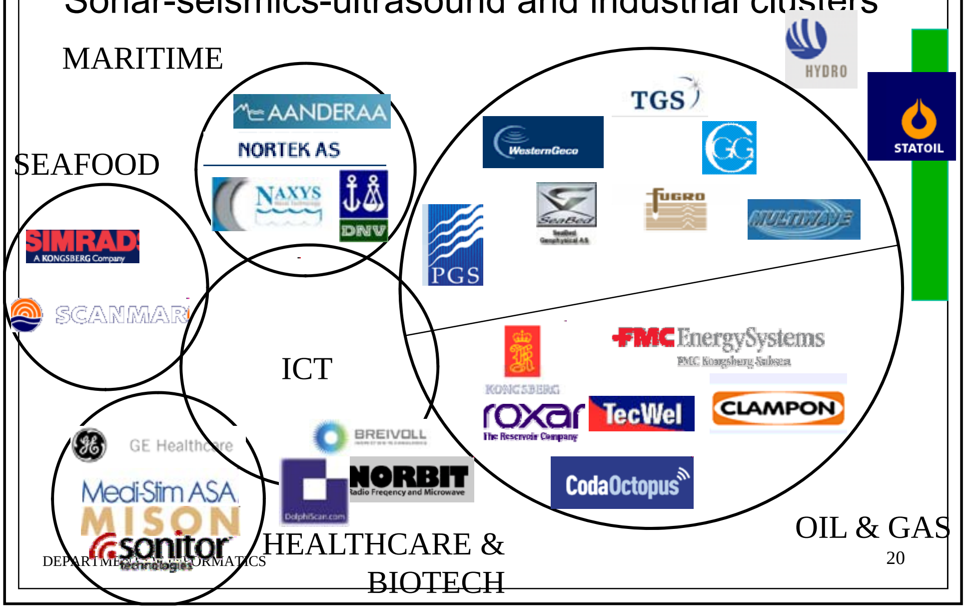
Sonar-seismics-ultrasound and industrial clusters



Centre of Imaging

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

Johnson & Dudgeon

- Goal of book: Give a strong foundation for approaching problems in
  - Acoustic signal processing
  - Sonar
  - Radar
- To a lesser extent:
  - Geophysical processing
  - Tomography
  - Computed imaging
  - Ultrasonic imaging
  - Communications

Chapters in Johnson & Dungeon

- Ch. 1: Introduction.
- Ch. 2: Signals in Space and Time.
  - Physics: Waves and wave equation.
    - c, λ, f, ω, k vector,...
    - Ideal and "real" conditions
- Ch. 3: Apertures and Arrays.
- Ch. 4: Beamforming.
  - Classical, time and frequency domain algorithms.
- Ch. 7: Estimation Theory
  - Assumed known: otherwise follow lectures in INF4480 in Stochastic processes and Estimation Theory
- Ch. 7: Adaptive Array Processing.

Ch. 1: Introduction: Array signal processing

- Goal of signal processing: To extract as much information as possible from our environment.
- Array Signal Processing: Branch of signal processing; focusing on signals conveyed by propagating waves.
- Array: a group of sensors located at distinct spatial locations.

= Gruppeantenne

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Goals of array processing

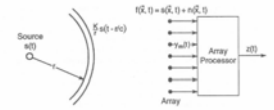

Figure 1.2 An array consists of a collection of sensors that spatiotemporally measure a wavefield $f(\vec{x}, t)$. These measurements are merged by the signal processing algorithm to accomplish some or all of the three goals described in the text. In some situations, the outputs of several arrays are merged for tracking the locations of the sources producing the propagating energy.

- Detection: To enhance the signal-to-noise ratio beyond that of a single sensor's output (problem 1.1).
- Signal characterization:
  - Directions to sources or its dual: speed of propagation = Imaging
  - The number of sources
  - Waveforms, temporal and spatial spectra
- Tracking:
  - Track the energy sources as they move in space.
  - E.g. ships approaching a harbour

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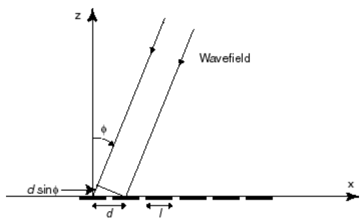
Array pattern = spatial frequency response



- Frequency response:

$$H(e^{j\omega T}) = \sum_{m=0}^{M-1} h_m e^{-jm\omega T}$$

- Sampling theorem:

$\omega \cdot T < \pi$

- Aperture smoothing function ($u=\sin\phi$):

$$W(u) = \sum_{m=0}^{M-1} w_m e^{-jm2\pi(u/\lambda)d}$$

- To avoid aliasing:

$$2\pi\frac{|u|}{\lambda}d = |k_x| \cdot d \leq \pi \Leftrightarrow d \leq \frac{\lambda}{2|\sin\phi|}$$

Array pattern for a regular 1-d array and a filter's frequency response

$$\begin{array}{ccc} \omega & \leftrightarrow & k_x = 2\pi\frac{\sin\phi}{\lambda} \\ T & \leftrightarrow & d \\ h_m & \leftrightarrow & w_m \end{array}$$

- The time-frequency sampling theorem $T < \pi/\omega_{max}$ translates into the spatial sampling theorem $d < \lambda_{min}/2$.

Signal processing

Johnson & Dudgeon, preface:

- We firmly believe that mathematics should be used to support and verify intuition, not substitute for it.

Signal Processing: Where physics and mathematics meet

Simon Haykin, IEEE Signal Processing Magazine, July 2001

Signal processing is at its best when it successfully combines ...

- the unique ability of mathematics to generalize ...
- with both the insight and prior information gained from the underlying physics of the problem at hand; ...
- the combination should lead to reliable algorithms that make a practical difference.

Signal Processing: Where physics and mathematics meet

Five ingredients essential for satisfactory performance:

1. Prior information
   - Understand the physical laws that govern the generation of the signals
2. Regularization
   - Embed prior information into algorithm design so as to stabilize the solution
3. Adaptivity
   - Learn from the operational environment so as to account for unknown statistics and nonstationary behavior
4. Robustness
   - Unavoidable disturbances are not magnified by the algorithm
5. Feedback
   - Powerful engineering principle with many beneficial effects: improved convergence, improved robustness, ...

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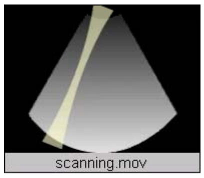
Echo imaging

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



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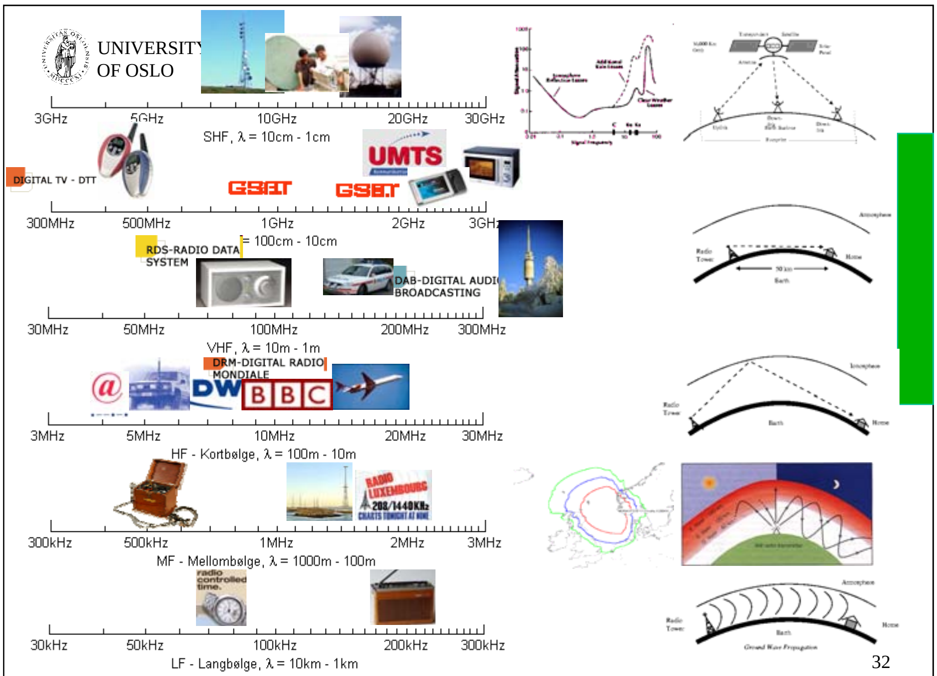

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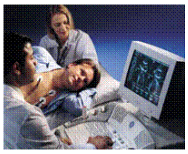
Sonars - Non-destructive testing, medical

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

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Narrowband – wideband

- Definition: Narrowband ⇔ relative bandwidth, B/f_0 < 10% of center frequency
- Most radio-based systems are narrowband
  - c is large, so frequency is high for reasonable λ, $c=\lambda \cdot f$
  - Therefore B is high even if B/f is small
  - E.g. remote sensing radar: 19 MHz/5.3 GHz = 0.35%
  - Exception: UWB – Ultra wide band, B>500 MHz (last ~5 – 10 years)
- Most acoustic systems are wideband
  - Hearing: 20 – 20 kHz ⇔ 3 decades
  - Medical ultrasound: 50 – 100% relative bandwidth centered on 2-10 MHz
  - Sonar is traditionally narrowband, is getting more wideband
- Consequence: time-delay or phase delay beamformers

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Near field – farfield

- Important applications operate in the near field:
  - Medical ultrasound
  - Seismics
  - Synthetic aperture radar and sonar

- Rule-of-thumb: Nearfield is characterized by a resolution which is smaller than the antenna

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Approximations (1) – must know!

McLaurin series:

- $\sin\theta = \theta - 1/3!\ \theta^3 + 1/5!\ \theta^5 - \ldots$
- $\cos\theta = 1 - 1/2!\ \theta^2 + 1/4!\ \theta^4 - \ldots$
- $\tan\theta = \theta + 1/3\ \theta^3 + 2/15\ \theta^5 + \ldots$

Small angle approximation – extensively used in mathematical physics:

- $\sin\theta \approx \tan\theta \approx \theta$
- $\cos\theta \approx 1$
- E.g. argument $\theta < 0.2$ rad $\approx 11.5^0$ =>
  - error in $\sin\theta$ is less than 0.7%
  - error in $\tan\theta$ less than 1.4%
  - error in $\cos\theta$ is less than 2%

Approximations (2) – must know!

- $(1+x)^{m/n} = 1+(n/m)\cdot x - n(m-n)/2!m^2\cdot x^2 + n(m-n)(2m-n)/3!m^3\cdot x^3 - \ldots$

Approximations for x<<1:

- $1/(1+x) = (1+x)^{-1} \approx 1 - x$
- $\sqrt{(1+x)} = (1+x)^{1/2} \approx 1 + x/2$
- $1/\sqrt{(1+x)} = (1+x)^{-1/2} \approx 1 - x/2$