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 electromagnetics 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
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

PhD course INF9410

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

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

Kongsberg Multibeam Echosounder

Blücher
Kongsberg Maritime: Hydroacoustic positioning reference - HPR

GE Vingmed Ultrasound
Fiber optic applications for streamer, seafloor and permanent

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
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.

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
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.
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
Goals of array processing

• 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

Array pattern = spatial frequency response

• Frequency response:
  \[ H(e^{j\omega T}) = \sum_{m=0}^{M-1} h_m e^{-j\omega T} \]

• Sampling theorem:
  \[ \omega \cdot T < \pi \]

• Aperture smoothing function (u=sinφ):
  \[ W(u) = \sum_{m=0}^{M-1} w_m e^{-jm\pi(u/\lambda)d} \]

• To avoid aliasing:
  \[ 2\pi \frac{|u|}{\lambda} d = |k_x| \cdot \pi \iff d \leq \frac{\lambda}{2|\sin \phi|} \]
Array pattern for a regular 1-d array and a filter's frequency response

\[ \omega \leftrightarrow k_x = 2\pi \frac{\sin \phi}{\lambda} \]
\[ T \leftrightarrow d \]
\[ h_m \leftrightarrow w_m \]

- The time-frequency sampling theorem \( T < \frac{\pi}{\omega_{\text{max}}} \) translates into the spatial sampling theorem \( d < \frac{\lambda_{\text{min}}}{2} \).

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


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.

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, ...
Echo imaging

- Radar
- Sonar
- Medical Ultrasound
- Non-destructive testing
- Send a ‘ping’
Sonars - Non-destructive testing, medical

Sonars, echosounders

Geophysical Geophysics: shallow seismic

Narrowband – wideband

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

Approximations (1) – must know!

McLaurin series:
• $\sin \theta = \theta - \frac{1}{3!} \theta^3 + \frac{1}{5!} \theta^5 - ...$
• $\cos \theta = 1 - \frac{1}{2!} \theta^2 + \frac{1}{4!} \theta^4 - ...$
• $\tan \theta = \theta + \frac{1}{3} \theta^3 + \frac{2}{15} \theta^5 + ...$

Small angle approximation – extensively used in mathematical physics:
• $\sin \theta \approx \tan \theta \approx \theta$
• $\cos \theta \approx 1$
• E.g. argument $\theta < 0.2 \text{ rad} \approx 11.5^\circ \Rightarrow$
  – 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!

- \((1+x)^{m/n} = 1 + \left(\frac{n}{m}\right)x - \frac{n(m-n)}{2!m^2}x^2 + \frac{n(n-m)(2m-n)}{3!m^3}x^3 - ...\)

Approximations for \(x<<1\):
- \(1/(1+x) = (1+x)^{-1} \approx 1 - x\)
- \(\sqrt{(1+x)} = (1+x)^{1/2} \approx 1 + x/2\)
- \(1/\sqrt{(1+x)} = (1+x)^{-1/2} \approx 1 - x/2\)