

Digital Signal Processing

Module 10: The End!

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Paolo Prandoni and Martin Vetterli
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- ▶ **Module 10.1:** Signal processing courses you can take from here
- ▶ **Module 10.2:** Some research projects that use techniques you learned here
- ▶ **Module 10.3:** Examples of start-ups that use signal processing as a core technology
- ▶ **Module 10.4:** Acknowledgements

Digital Signal Processing

Module 10.1: Signal processing courses you can take from here

- ▶ Statistical Signal Processing
- ▶ Signal Processing for Audio and Acoustics
- ▶ Mathematical Foundations of Signal Processing
- ▶ Advanced Topics in Signal Processing

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- ▶ Statistical Signal Processing
- ▶ Signal Processing for Audio and Acoustics
- ▶ Mathematical Foundations of Signal Processing
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Why do we need statistical tools to process signals?

- ▶ Real life measurements can often be modelled as a stochastic process, taking into account uncertainties and noise
- ▶ Processing methods might have to adapt to changing conditions
- ▶ Optimal estimation of specific characteristics of a signal requires specific stochastic models and statistical techniques

What are the problems we want to address?

- ▶ Spectral estimation for Wireless Transmissions, Biomedical Signals, Audio Signals
- ▶ Classification of Neurobiological Spikes
- ▶ Adaptive filtering for echo cancellation in Voice-Over-IP transmissions

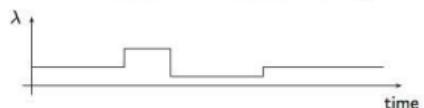
An exemplary application:

**Measurements of the antenna lobe
neural activity of a grasshopper**



**Poisson model
driven by a
Markov Chain**

**Characterization of
the Neural Activity**



Principal Component Analysis

**Classification of the
Neural Spikes**



Outline of the class

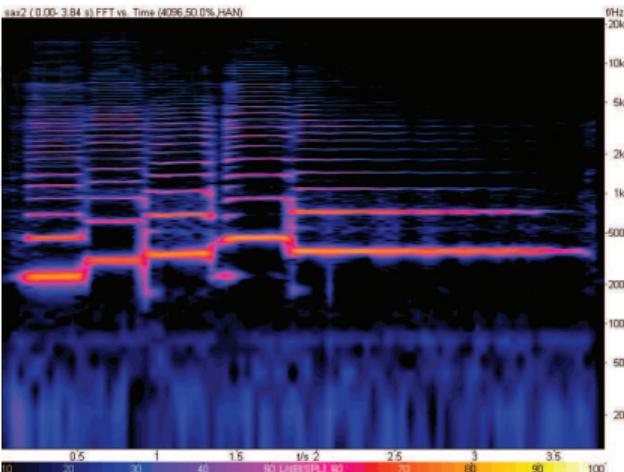
- ▶ Basic models and methods
- ▶ Statistical Signal Processing Tools for
 - Wireless Transmissions
 - Echo Cancellation
 - Neurobiological Spikes

Website of the class

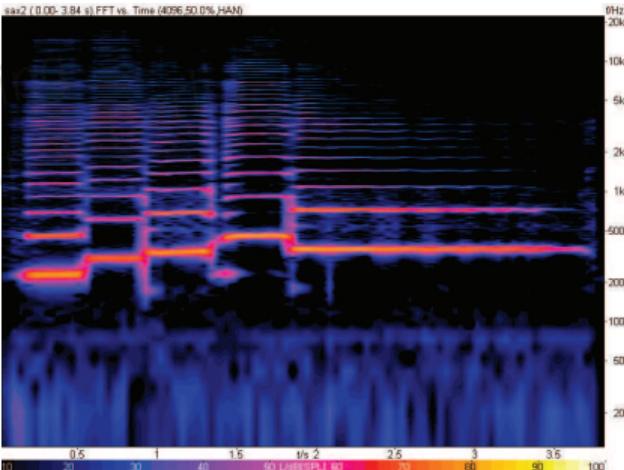
- ▶ http://lcav.epfl.ch/teaching/statistical_sp_applications

► The objective of the course is to understand

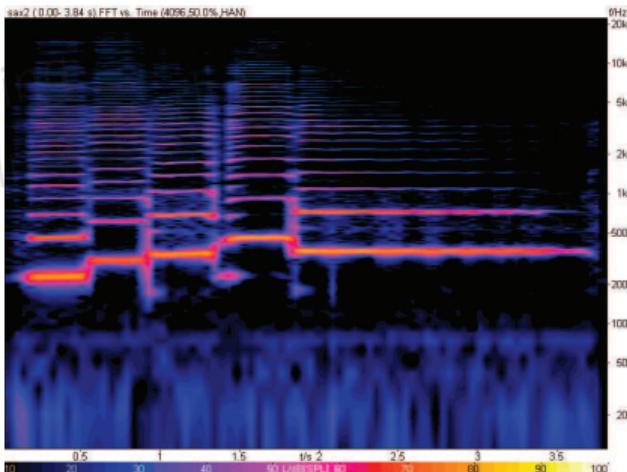
- fundamental theories of acoustics and psychoacoustics
- the process of spatial hearing and spatial audio reproduction
- the manipulation and processing of audio signals (filtering, delaying and other spectral modifications)
- state-of-the-art techniques used in pro audio and consumer audio



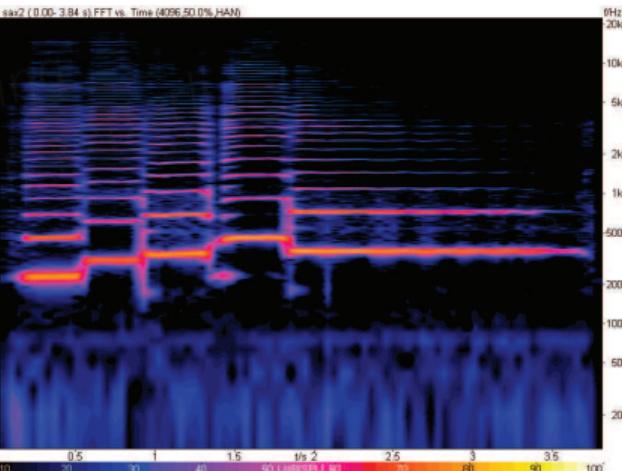
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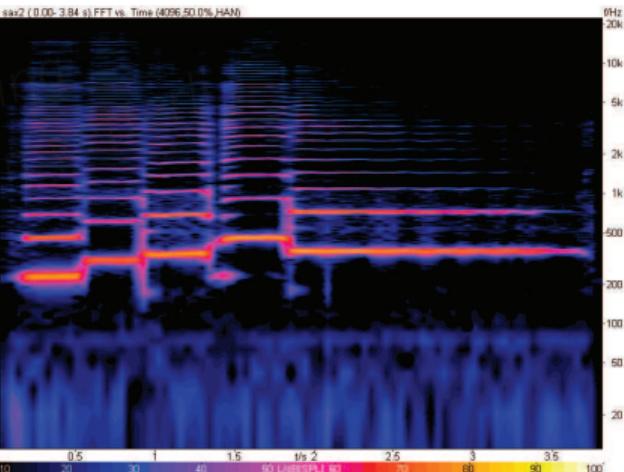
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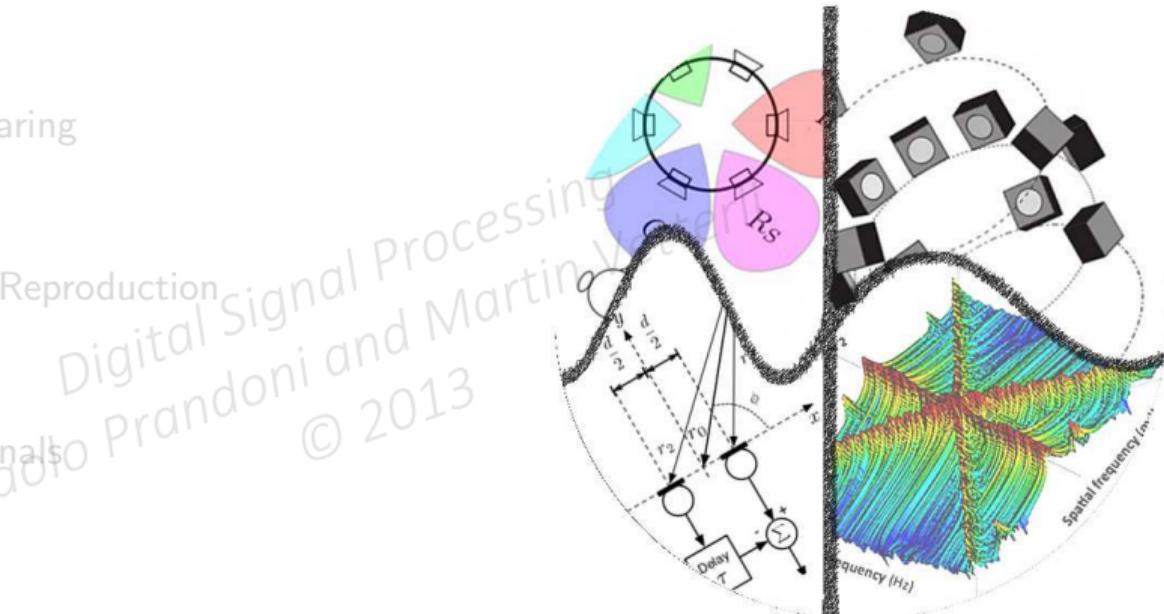


- ▶ Auralization - rendering audible (imaginary) sound fields



► Outline of the class

- Basics of Spatial Hearing
- Audio Recording
- Multichannel Audio Reproduction
- Spatial Filtering
- Coding of Audio Signals
- Auralization

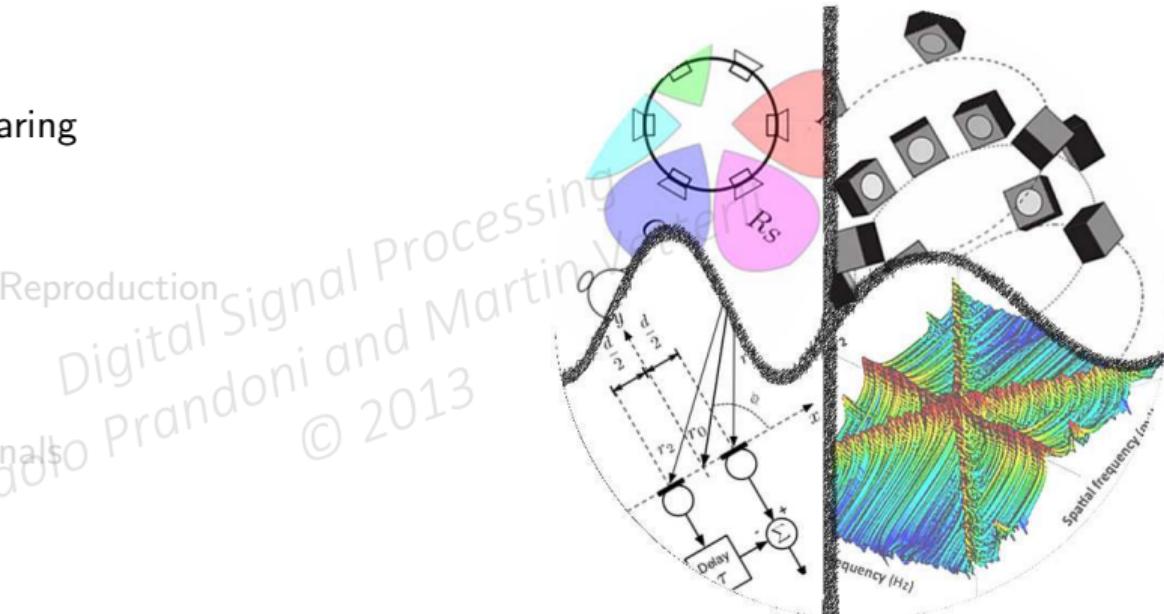


► Details on course website

http://lcav.epfl.ch/teaching/sp_for_audio_and_acoustics

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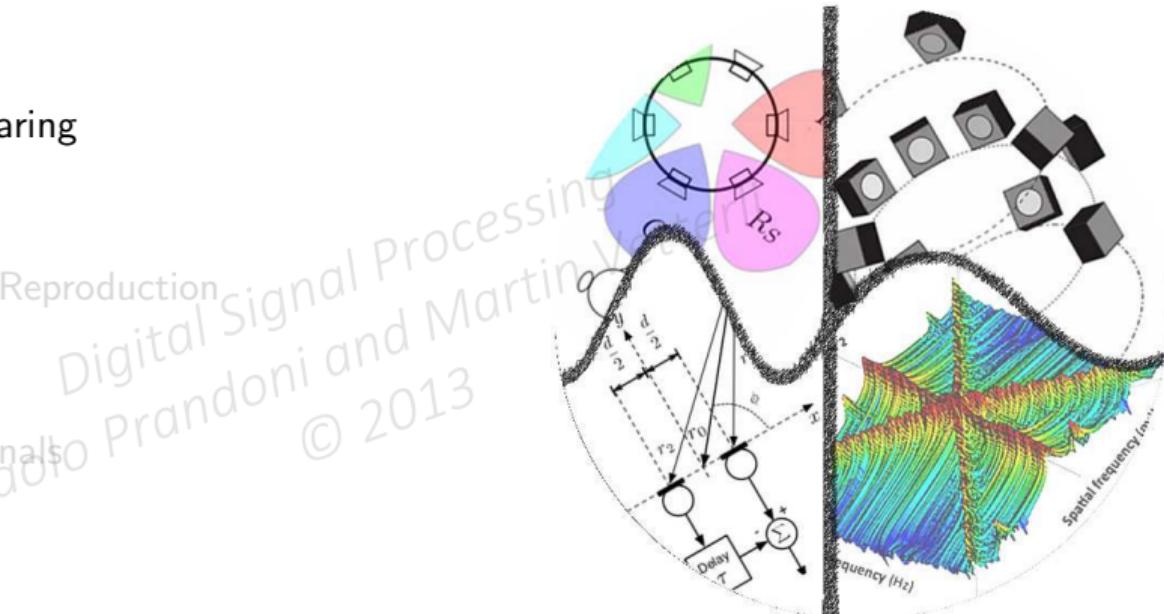


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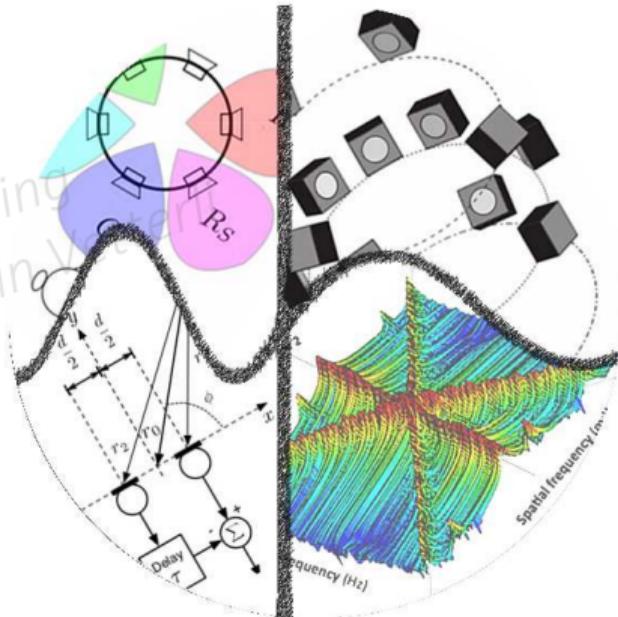
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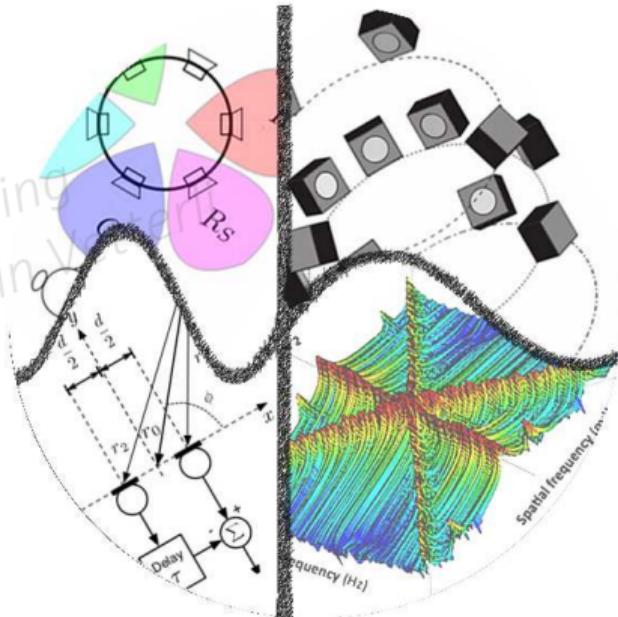


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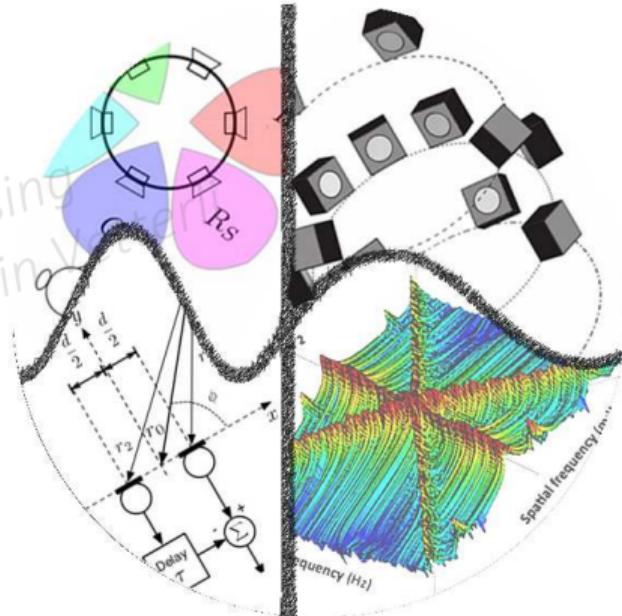


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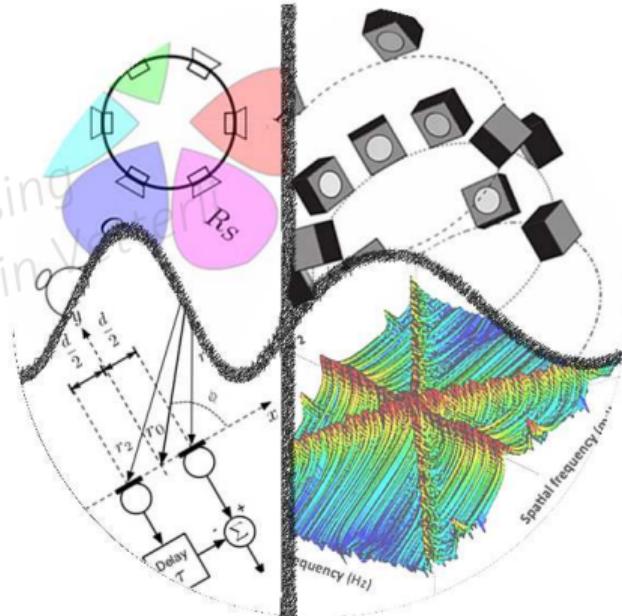


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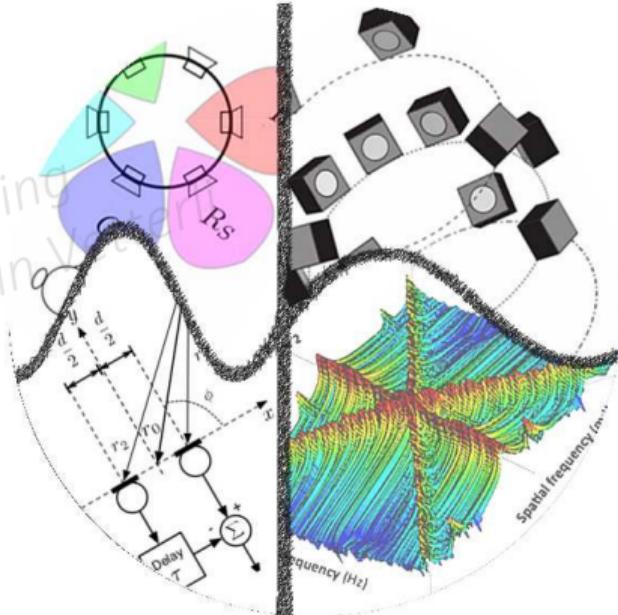


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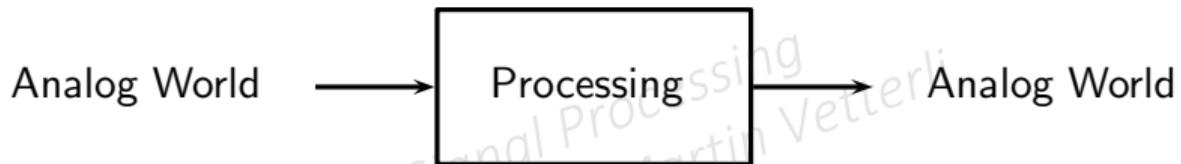
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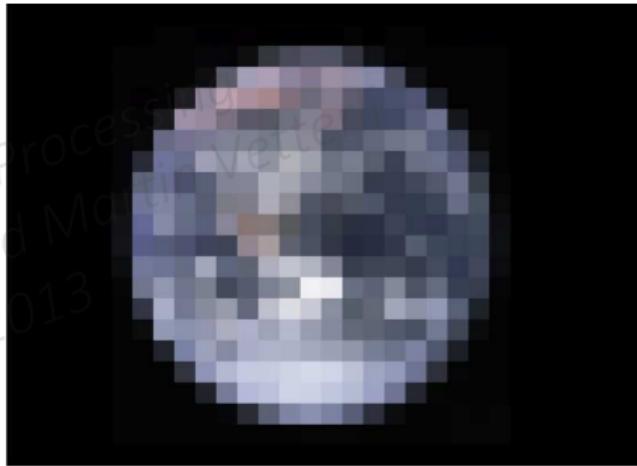
- ▶ The world is analog but computation is digital
- ▶ How to go between these representations?



Ex: Audio, sensing, imaging, computer graphics, simulations etc

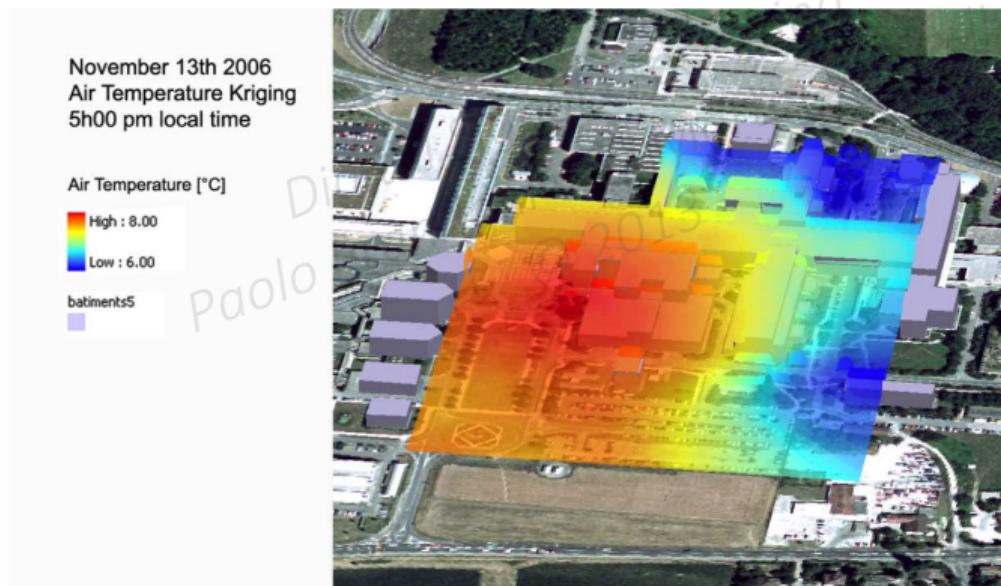
- ▶ Key mathematical concepts:
 - Sampling and interpolation
 - Approximation and compression

From Analog to Digital



Example: sensor networks for environmental monitoring

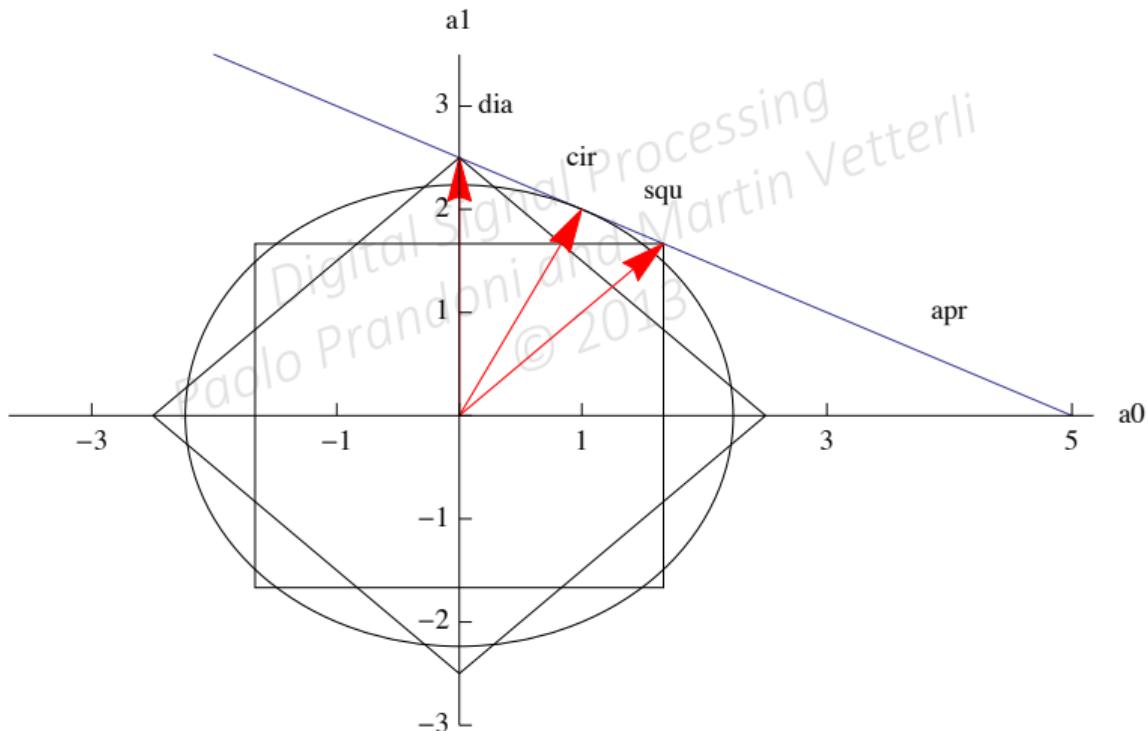
- ▶ How many sensors?
- ▶ How to reconstruct?



- ▶ Brief outline:
 1. From Euclid to Hilbert
 2. Sequences and Discrete-Time Systems
 3. Functions and Continuous-Time Systems
 4. Sampling, Interpolation and Approximation
 5. Applications
- ▶ Details on course website
 - http://lcav.epfl.ch/SP_Foundations
 - <http://moodle.epfl.ch/course/view.php?id=13431>
- ▶ Textbook: M. Vetterli, J. Kovacevic and V. Goyal, “Foundations of Signal Processing”, Cambridge U. Press, 2013. Available in open access at
 - <http://www.fourierandwavelets.org>

- ▶ Models and methods used for describing and processing signals arising from physical phenomena constantly increase in complexity
- ▶ Classical approaches are not sufficient anymore, since they either cannot be applied, or they lead to wrong results or to labyrinthian computations
- ▶ Advanced tools are required to optimally model and analyse the data

Compressed Sensing Example: Expansion with respect to an overcomplete set of vectors is not unique. One can optimize various norms (l_1, l_2, l_∞)



The course proposes every year one of the following topics

- ▶ Fourier and wavelets signal processing
- ▶ Mathematical principles of signal processing
- ▶ Selected current topics in signal processing
(sparse signal processing, signal processing for sensor networks, etc.)

Website and textbook of the class

- ▶ http://lcav.epfl.ch/teaching/advanced_sp
- ▶ Volume 2 of <http://www.fourierandwavelets.org>

END OF MODULE 10.1

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Digital Signal Processing

Module 10.2: Some research projects that use techniques you learned here

Overview:

- ▶ eFacsimile or art work acquisition, representation and rendering
- ▶ Signal processing for sensors networks
- ▶ Source localization in graphs
- ▶ Finite rate of innovation sampling
- ▶ Sampling of fields
- ▶ Image acquisition using oversampled binary pixels
- ▶ Predicting the stock market
- ▶ Inversion of the diffusion equation
- ▶ The Fukushima inverse problem
- ▶ Can you hear the shape of a room

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People involved:

- ▶ Joint project between LCAV and Google Inc.
- ▶ Dr. Loïc Baboulaz
- ▶ Ms. Mitra Fatemi
- ▶ Mr. Niranjan Thanikachalam
- ▶ Mr. Zhou Xue

What are the problems addressed?

- ▶ How to capture, represent and render an Artwork faithfully?
- ▶ How to achieve relighting, 3D manipulation and high-resolution on mobile devices?

Demo: interactive relighting and manipulation of Oil Paintings and Stained Glasses



What tools used?

- ▶ Traditional and light-field cameras
- ▶ Light transport theory
- ▶ Sparse recovery methods

Websites

- ▶ <http://lcav.epfl.ch/cms/site/lcav/lang/en/efacsimile>
- ▶ <http://www.youtube.com/user/lcavepfl>

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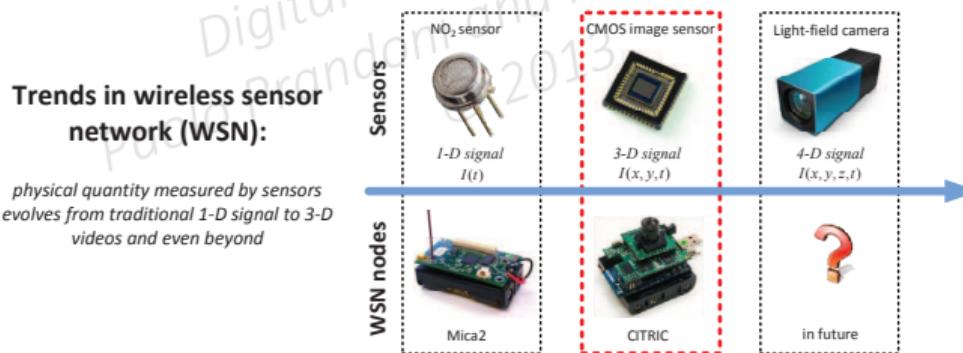
Visual Monitoring using Wireless Sensor Networks

People involved:

- ▶ Zichong Chen, Guillermo Barrenetxea, Martin Vetterli

Video monitoring with autonomous wireless camera nodes. Challenges include:

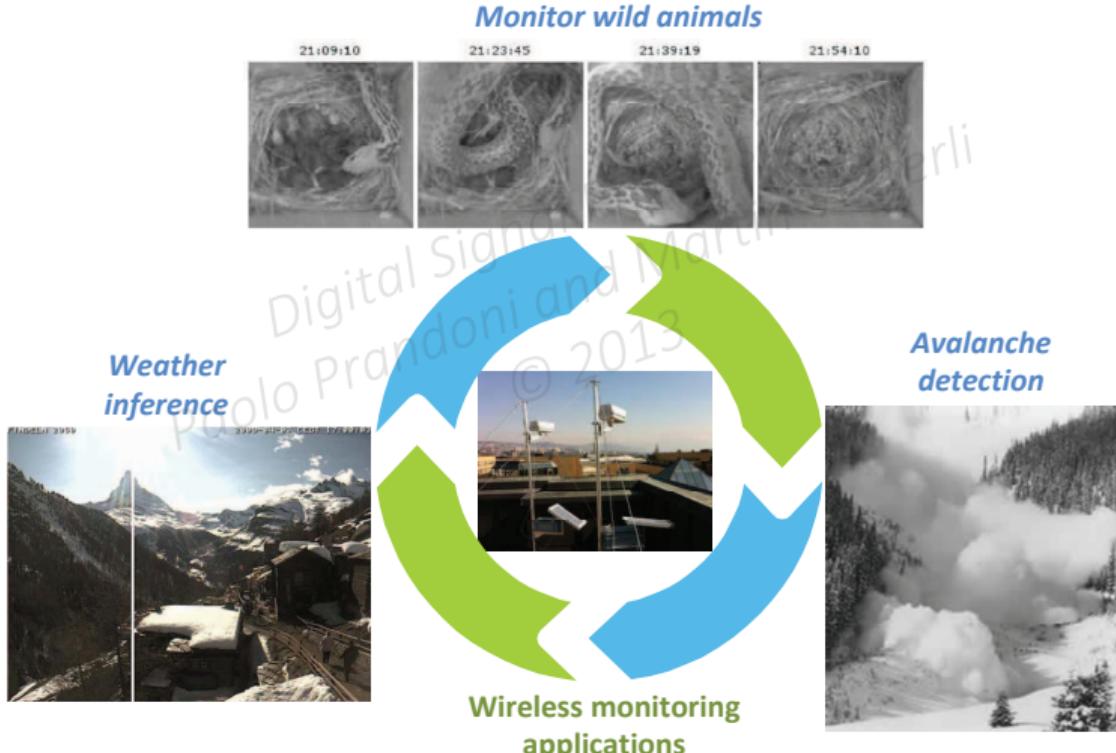
- ▶ Each node has very limited energy (e.g., 100 mW from solar panel)
- ▶ Need to capture, process and transmit 3-D signals (e.g., 900 kilobytes per image), which requires far more energy than the budget



Tools for better representing and understanding image signals: **image compression** (low level), **computer vision** (high level)

Visual Monitoring using Wireless Sensor Networks

- ▶ Many real-world applications by using wireless cameras



Results so far

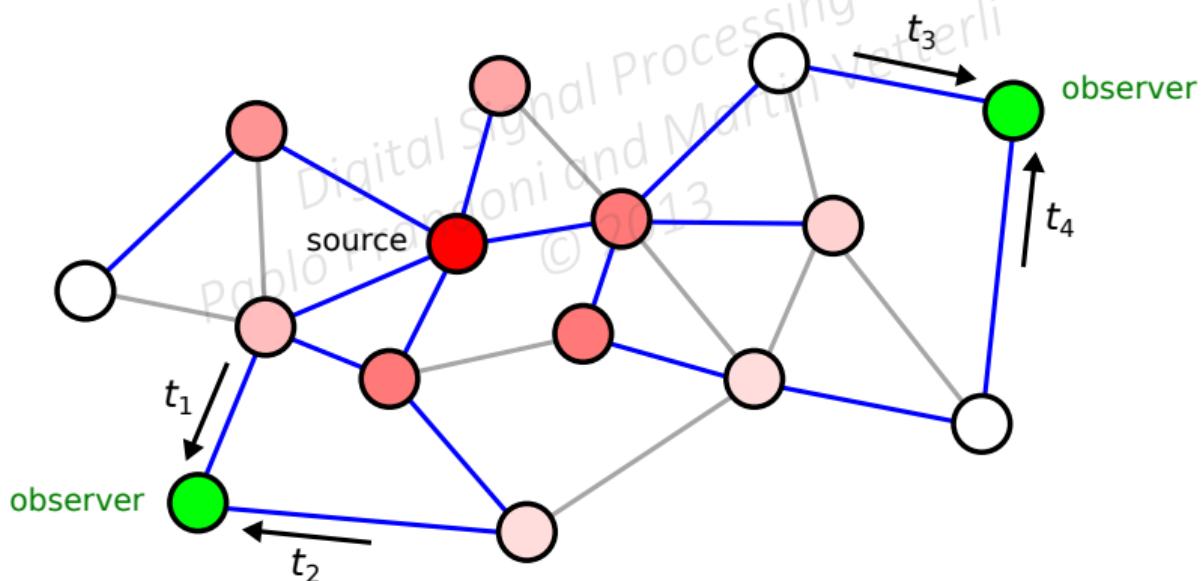
- ▶ N cameras can collaboratively share the monitoring task and reduce energy per node by a factor of N
- ▶ Understanding video content via computer vision techniques improves video compression efficiency by 70% over conventional H.264 codec

Further references

- ▶ Thesis on Cooperative Visual Monitoring in Energy-Constrained Wireless Sensor Networks: <http://infoscience.epfl.ch/record/183072>
- ▶ Supported by the grant from NCCR-MICS, <http://www.mics.org>

People involved: Dr Pedro Pinto, Prof Patrick Thiran

- ▶ Goal: Locate the source of diffusion in a network with thousands of nodes
- ▶ Challenges: Observer are sparsely-placed, have only time-of-arrivals



Our contributions:

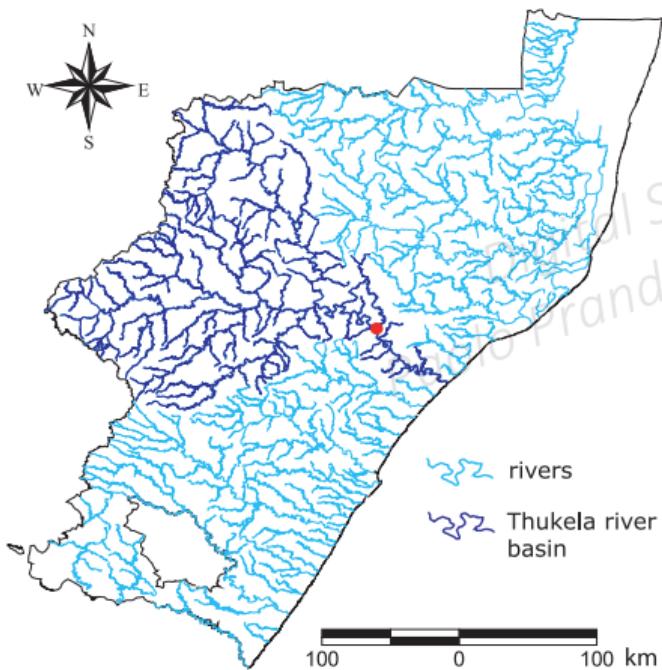
- ▶ Developed optimal and efficient algorithms that exploit time-of-arrivals.
- ▶ Achieve 90% accuracy with typically less than 20% observers.
- ▶ "Locating the Source of Diffusion in Large-Scale Networks", P. Pinto, P. Thiran, M. Vetterli, Physical Review Letters, Aug. 2012.
- ▶ Project funded by the Bill and Melinda Gates Foundation.

Future directions:

- ▶ Optimal placement of observers.
- ▶ Disease control and public health.
- ▶ Social media analytics.

Applications

- ▶ Cholera outbreak in the KwaZulu-Natal province, South Africa, 2001



- ▶ Airborne contamination of transportation infrastructure (NYC subway)



Finite Rate of Innovation (FRI)

People involved:

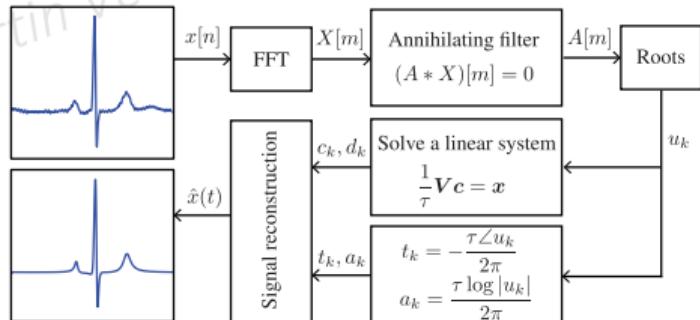
- ▶ Dr. Nikolaos Freris, Senior Scientist
- ▶ Gilles Baechler, Doctoral Assistant
- ▶ Ehsaneddin Asgari, M.Sc. Assistant
- ▶ Orhan Öcal, M.Sc. Assistant

What is FRI?

- ▶ Sampling and reconstruction of signals with a **finite number of parameters** (per unit of time)
- ▶ Typical signals: periodic streams of Dirac pulses, periodic non-uniform splines

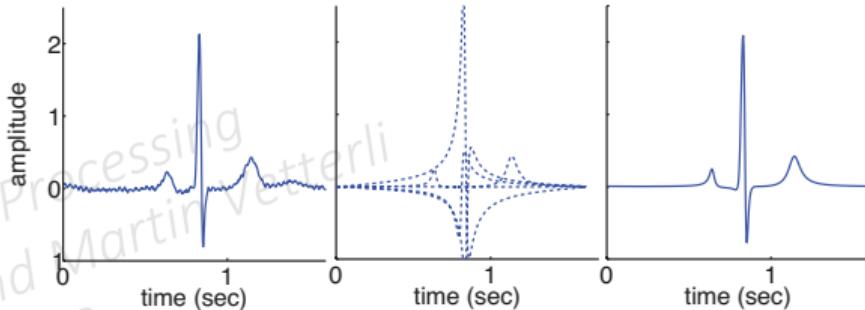
DSP Tools

- ▶ Fast Fourier Transform
- ▶ Singular Value Decomposition
- ▶ **Annihilating filter** (root finding for complex exponentials)



Variable Pulse Width (VPW)

- ▶ Extension of FRI to a wider range of waveforms
- ▶ Model signals as a sum of asymmetric pulses



Industrial Collaborator



Advantages

- ▶ Compression
- ▶ Noise removal

- ▶ M. Vetterli, P. Marziliano, and T. Blu. Sampling Signals With Finite Rate of Innovation. IEEE Transactions on Signal Processing, vol. 50, no. 6, June 2002.
- ▶ G. Baechler, N. Freris, R.F.Quick, and R.E. Crochiere. Finite rate of innovation based modeling and compression of ECG signals. ICASSP 2013.
- ▶ Hormati, A., Vetterli, M., Compressive Sampling of Multiple Sparse Signals Having Common Support Using Finite Rate of Innovation Principles, Signal Processing Letters, IEEE, vol.18, no.5, pp.331,334, May 2011.
- ▶ Y. Barbotin and M. Vetterli. Fast and Robust Parametric Estimation of Jointly Sparse Channels, in Journal on Emerging and Selected Topics in Circuits and Systems, IEEE, vol. PP, num. 99, p. 1-11, 2012.
- ▶ A. Hormati and M. Vetterli. Distributed Compressed Sensing: Sparsity Models and Reconstruction Algorithms Using Annihilating Filter. ICASSP, Las Vegas, Nevada, USA, March 30-April 4, 2008.

People involved:

- ▶ Jayakrishnan Unnikrishnan
- ▶ Martin Vetterli

Research challenges

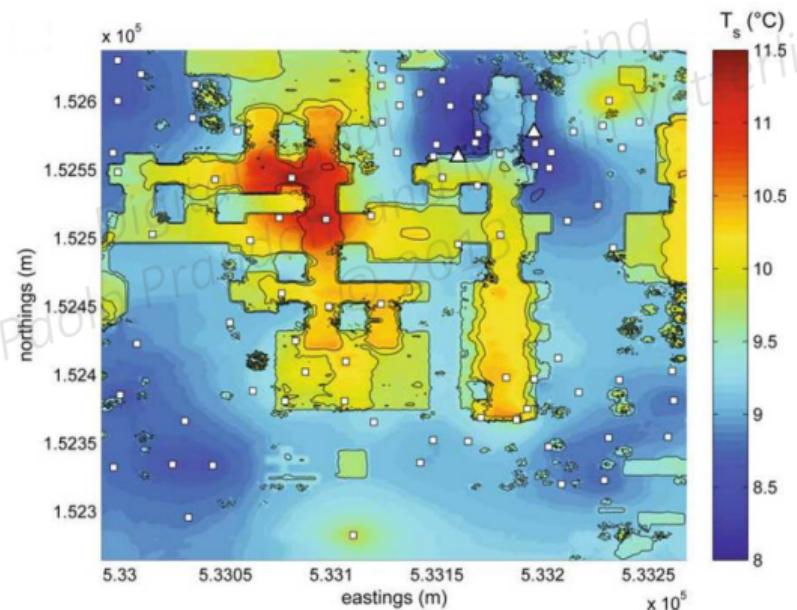
- ▶ Algorithms for reconstructing a spatial field using discrete measurements taken by sensors
- ▶ Sampling spatial fields with mobile sensors
 - Design of efficient sensor trajectories that minimize the total distance traveled by the sensors
 - Spatial processing via time-domain filtering

Tools used

- ▶ Classical sampling theory and Fourier analysis in higher dimensions

Sampling spatial fields using mobile sensors 2/3

Application: Surface temperature measurement in EPFL campus



Insights from research

- ▶ Sampling along equispaced parallel lines (see figure) is optimal over a wide range of configurations of sensor trajectories for 2D low-pass fields
- ▶ Spatial anti-aliasing can be induced by using mobile sensors with time-domain filtering



Key papers available at <http://lcav.epfl.ch/people/jayakrishnan.unnikrishnan>

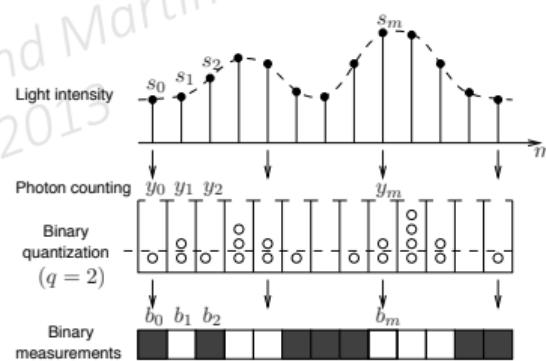
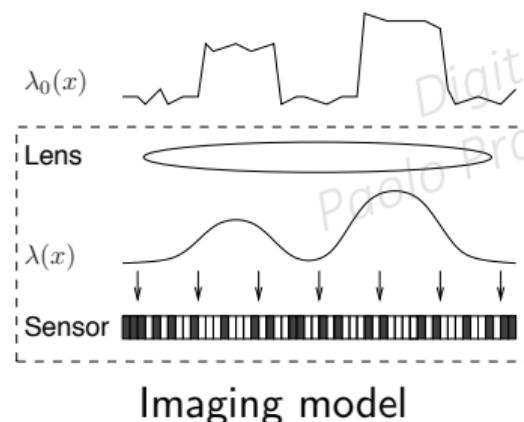
- ▶ J. Unnikrishnan and M. Vetterli, "Sampling High-Dimensional Bandlimited Fields on Low-Dimensional Manifolds" accepted for publication in IEEE Transactions on Information Theory, Oct 2012.
- ▶ J. Unnikrishnan and M. Vetterli, "Sampling and Reconstruction of Spatial Fields using Mobile Sensors" accepted for publication in IEEE Transactions on Signal Processing, Feb 2013.

People involved:

- ▶ Feng Yang, Luciano Sbaiz (Google Zürich), Yue M. Lu (Harvard University), Sabine Süsstrunk, Hyungjune Yoon, Edoardo Charbon, Martin Vetterli

What are the problems addressed?

- ▶ Propose an image sensor with binary pixels, used for high dynamic range imaging

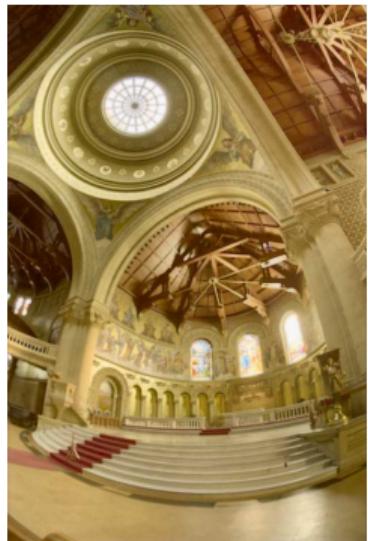


- ▶ Reconstruct the light intensity field from binary measurements

Image acquisition using oversampled binary pixels 2/3

Experimental results

- ▶ Synthetic image



Spatial: 64×64
Temporal: 64

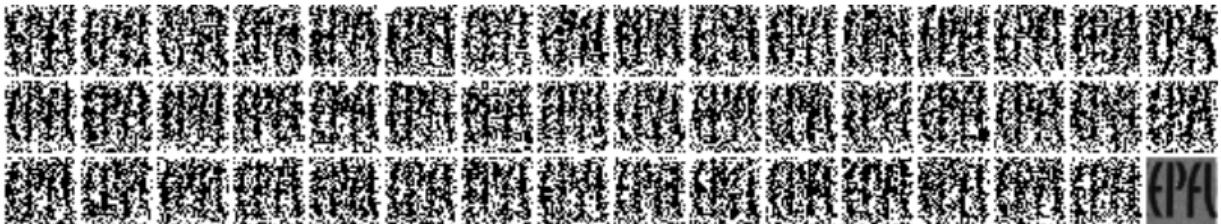
- ▶ Read sensor data

Single-photon avalanche diode (SPAD) camera



Pixel value: binary
Sensitivity: single photon
Resolution: 32×32
Temporal oversampling to emulate spatial oversampling

Reconstruction from 4096 consecutive frames



Main publications

- ▶ Feng Yang, Yue M. Lu, Luciano Sbaiz, and Martin Vetterli. Bits from photons: Oversampled image acquisition using binary Poisson statistics. *IEEE Transactions on Image Processing*, vol. 21, issue 4, pp. 1421-1436, 2012.
- ▶ Feng Yang, Martin Vetterli. Oversampled noisy binary image sensor. *Proc. of IEEE Int. Conference on Acoustics, Speech and Signal Processing*, Vancouver, May 26-31, 2013.
- ▶ Luciano Sbaiz, Feng Yang, Edoardo Charbon, Sabine Süsstrunk, and Martin Vetterli. The gigavision camera. In *Proc. of IEEE Int. Conference on Acoustics, Speech and Signal Processing*, pp.1093-1096, Taipei, Apr. 2009.

Website and other pointers

- ▶ Feng Yang's PhD thesis <http://infoscience.epfl.ch/record/174695?ln=en>
- ▶ <http://lcav.epfl.ch/research/gigavision>

People involved:

- ▶ Lionel Coulot
- ▶ Peter Bossaerts

What are the problems addressed?

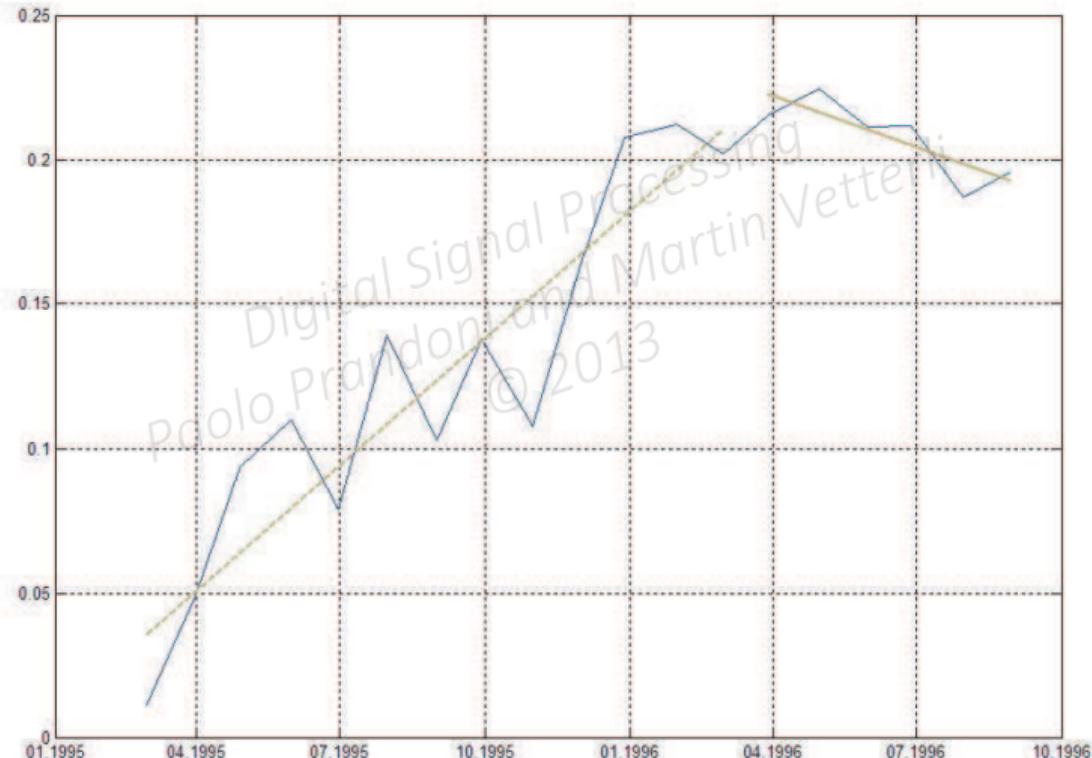
- ▶ prediction means identifying features in observed data and extrapolating them in the future in the hope they persist
- ▶ features expressed using statistical models that account for the inherent randomness in data
- ▶ how do we decide between a simple and a more complex model?
- ▶ on which portion of the observed data do we learn the model?

What tools used?

- ▶ coding theory
- ▶ dynamic programming

Predicting the stock market

An exemplary application: dynamic trend line



Results so far

- ▶ project completed

Website and other pointers

- ▶ PhD thesis
- ▶ <http://infoscience.epfl.ch/record/182936>
- ▶ Sponsor
- ▶ <http://www.lgt.com>

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People involved:

- ▶ Juri Ranieri, Ivan Dokmanić, Amina Chebira, Yue Lu, Martin Vetterli

What are the problems addressed?

- ▶ Model for many physical phenomena: temperature, atmospheric dispersion, ...
- ▶ We measure the field at certain locations in space and time
- ▶ Target: estimate the sources of the field
- ▶ Variations: advective diffusive phenomena, time varying sources, ...

What tools used?

- ▶ Fourier analysis, Signals with Finite Rate of Innovation, Compressive Sensing

Inversion of the diffusion equation 2/3



An exemplary application: estimation of time-varying atmospheric emissions

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What we have shown so far

- ▶ Recovery spatially sparse sources appearing at unknown time
- ▶ Recovery of time-varying emissions with FRI
- ▶ Recovery of the field using traditional sampling technique exploiting the low-pass kernel

Main Publications

- ▶ J. Ranieri, Y. Lu, A. Chebira and M. Vetterli. *Sampling and Reconstructing Diffusion Fields with Localized Sources*
- ▶ I. Dokmanic, J. Ranieri, A. Chebira and M. Vetterli. *Sensor Networks for Diffusion Fields: Detection of Sources in Space and Time*
- ▶ J. Ranieri, I. Dokmanic, A. Chebira and M. Vetterli. *Sampling and Reconstruction of Time-Varying Atmospheric Emissions*
- ▶ J. Ranieri and M. Vetterli. *Sampling and reconstructing diffusion fields in presence of aliasing*

People involved:

- ▶ Marta Martinez-Camara, Ivan Dokmanic, Juri Ranieri, Robin Scheibler, Martin Vetterli.
- ▶ Andreas Stohl, from NILU, Norway.

What are the problems addressed?

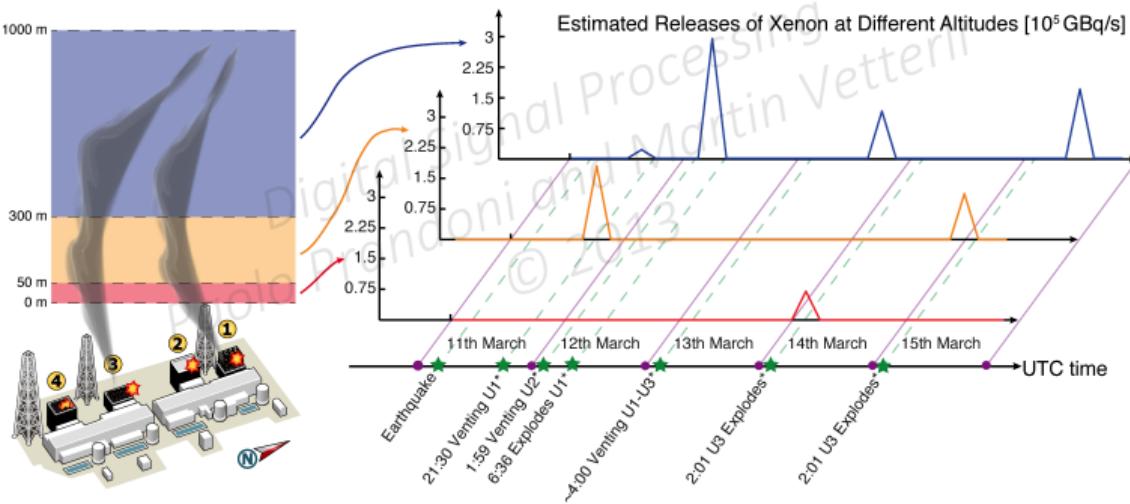
- ▶ We want to estimate the emissions of radionucleides during a nuclear accident.
- ▶ Using a few sensors located all around the world.

What tools used?

- ▶ Sparse regularizations.
- ▶ Atmospheric dispersion models.

The Fukushima Inverse Problem 2/3

An example application: Estimation of Xenon emissions from Fukushima.



Something about the results so far

- ▶ We estimated the Xenon emissions from Fukushima without using any a priori information.
- ▶ We showed that all the Xenon accumulated in the nuclear power plant before the accident was released in the first 5 days after the earthquake.

Website and other pointers

- ▶ <http://infoscience.epfl.ch/record/182697>
- ▶ M.Martinez-Camara, I.Dokmanic, J.Ranieri, R.Scheibler, M. Vetterli, A.Stohl, "The Fukushima Inverse Problem," Proc IEEE ICASSP, May 2013.

Can One Hear the Shape of a Room?

- ▶ People: Ivan Dokmanić, Reza Parhizkar, Andreas Walther, Martin Vetterli and Yue M. Lu (Harvard School of Engineering)
- ▶ Remember 5.12: Dereverberation and Echo Cancelation?
- ▶ If you know “room shape” you can get rid of the echoes
- ▶ If you know the shape... but can we know it?
- ▶ *Imagine you're blindfolded inside an unknown room and you snap your fingers. Can you hear the shape of the room?*

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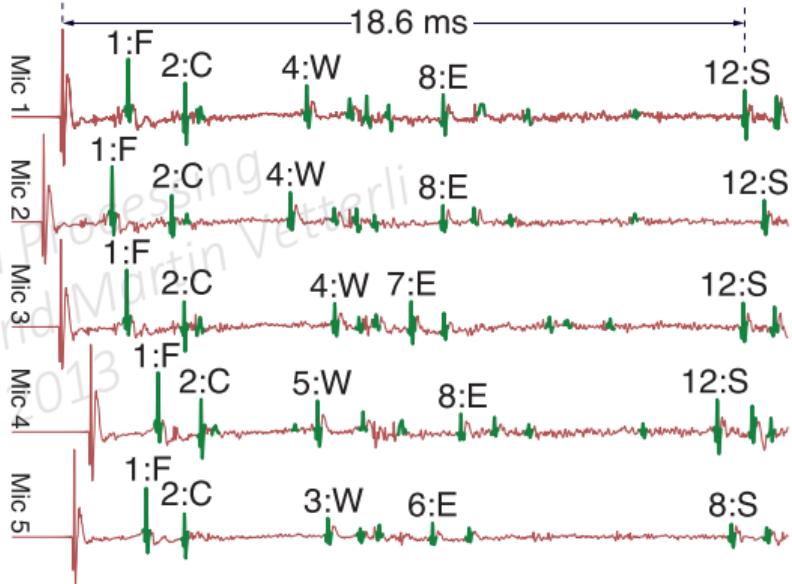
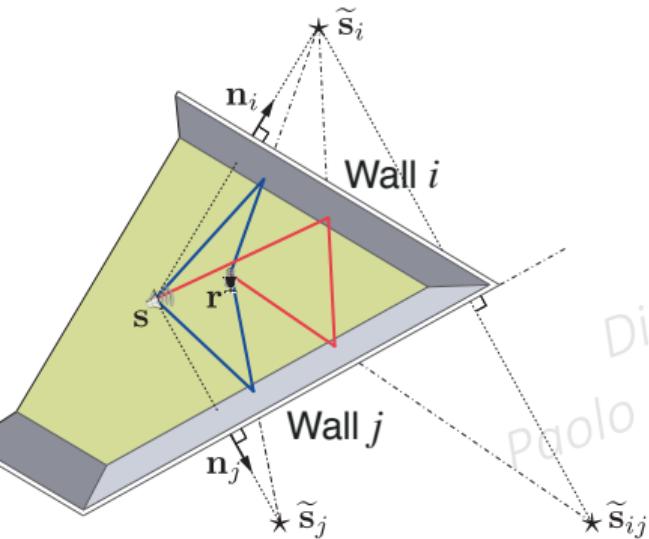
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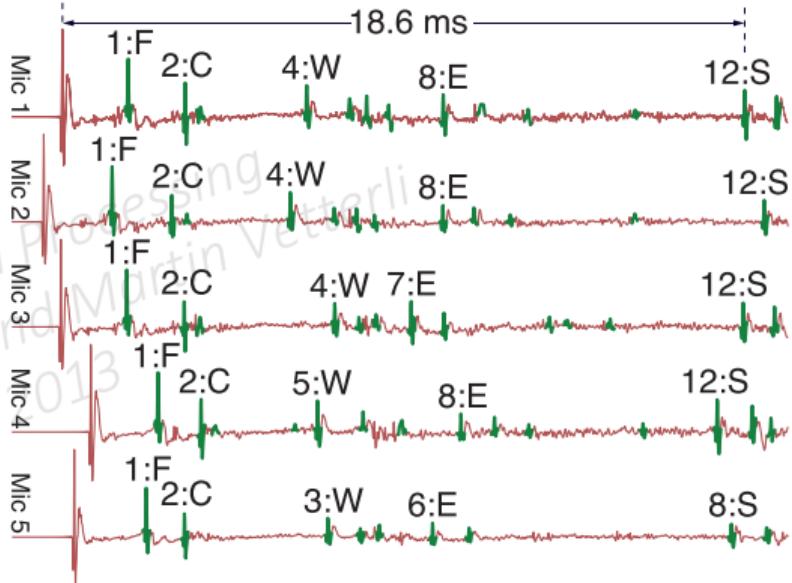
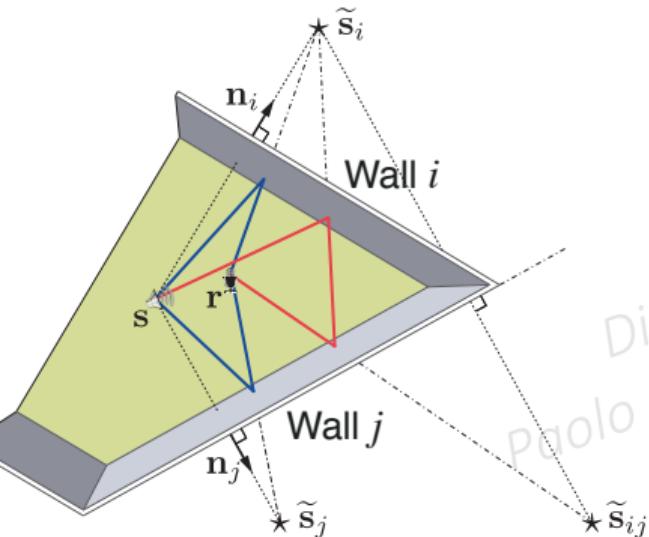
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How Does One Hear the Room?

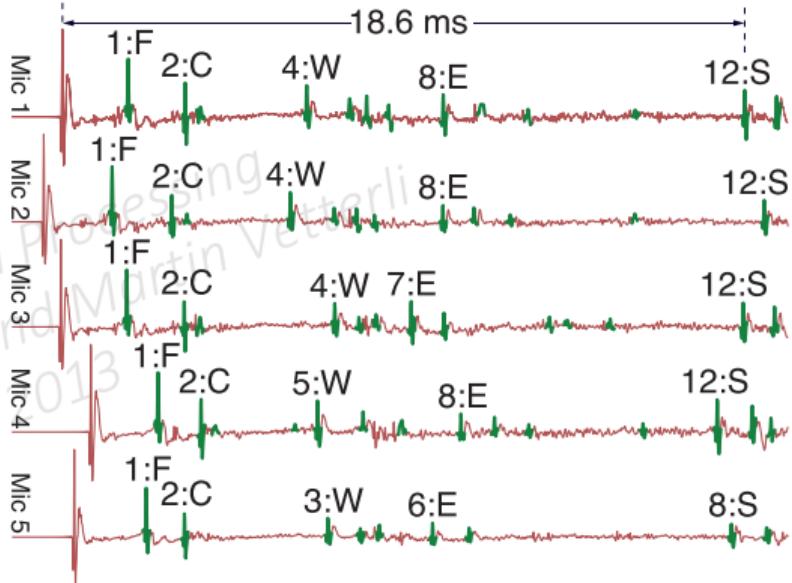
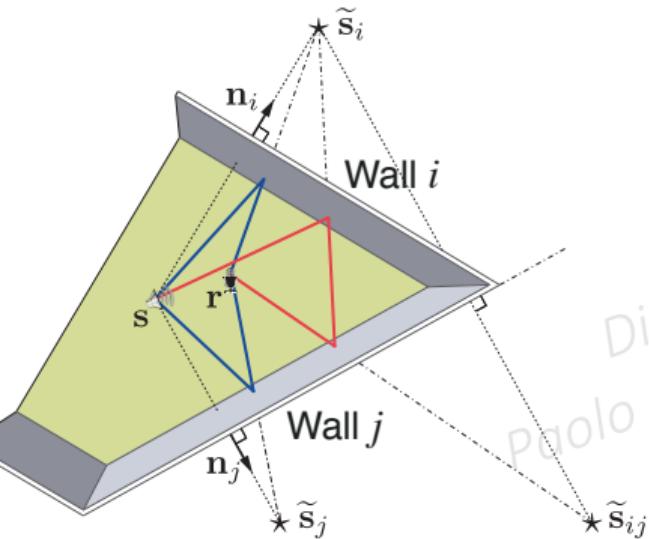


- ▶ Aim: Reconstruct the shape of the room from acoustic responses (as few as possible!)
- ▶ How many suffice? We can get a *robust* algorithm with 4!

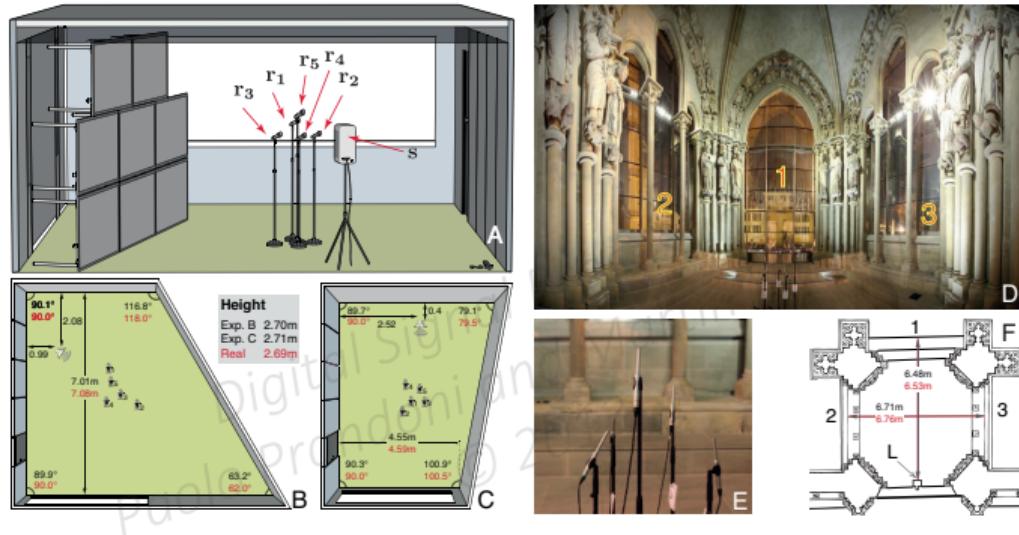
How Does One Hear the Room?



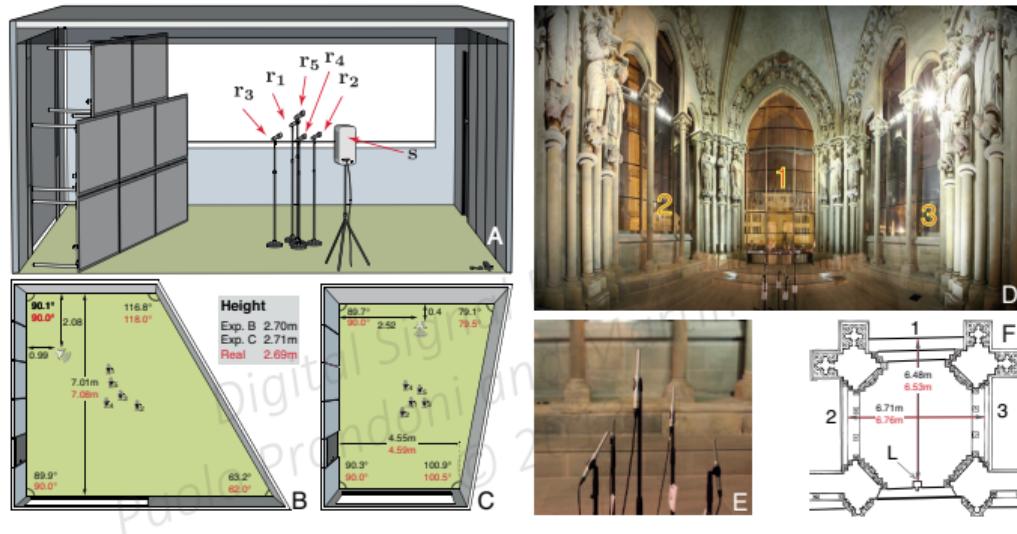
How Does One Hear the Room?



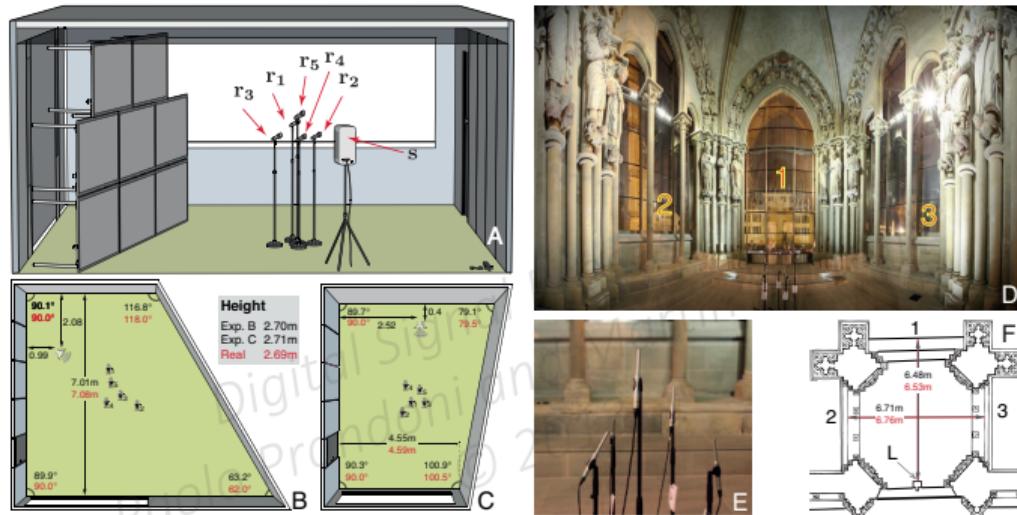
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- ▶ Exploiting the geometry of echoes we get stunning results
- ▶ One *can* hear the shape of a room!
- ▶ For more info & publications, visit <http://lcav.epfl.ch/people/ivan.dokmanic>



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Digital Signal Processing

Module 10.3: Examples of start-ups that use signal processing as a core technology

- ▶ Illusonic
- ▶ Quivid
- ▶ Sensorscope
- ▶ Vidinoti

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Overview:

- ▶ Illusonic
- ▶ Quivid
- ▶ Sensorscope
- ▶ Vidinoti

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Overview:

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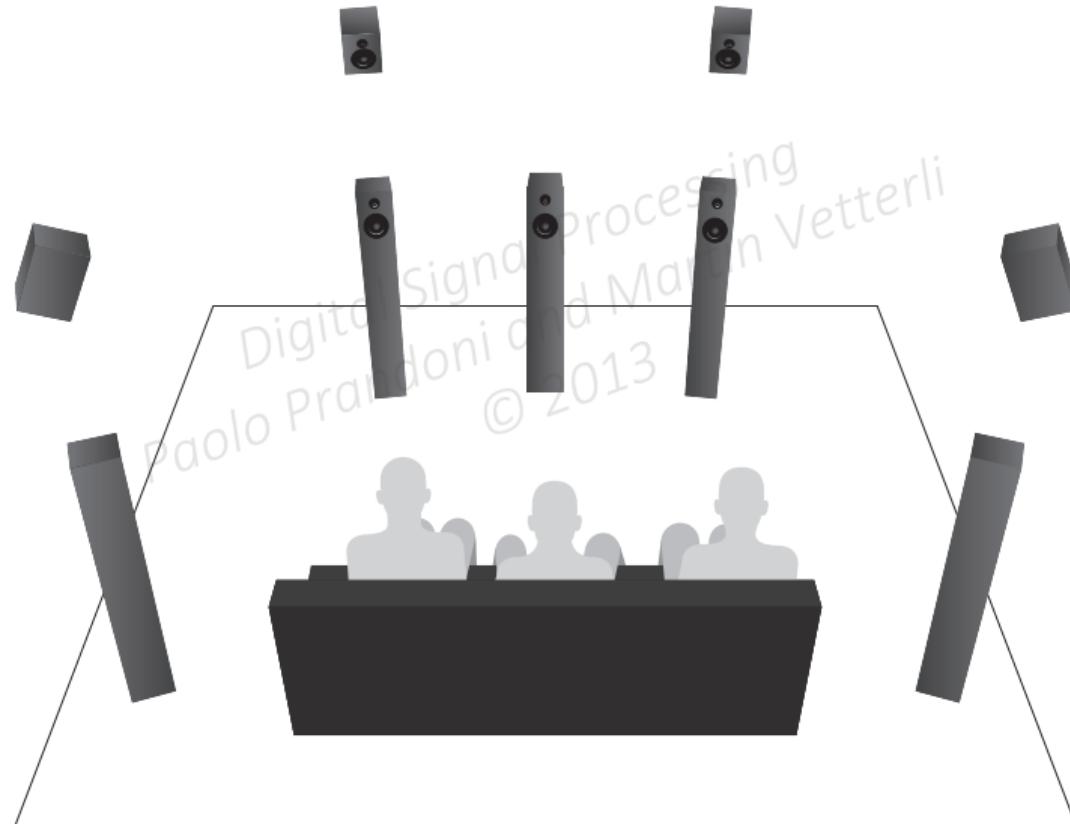
What are the problems addressed?

- ▶ Acoustic signal processing (beamforming, echo control, soundbar, ...)
- ▶ Spatial audio processing (3D audio, upmix, effects, ...)
- ▶ Audio engineering tools (de-reverb, de-noise, ...)
- ▶ etc

What tools used?

- ▶ Digital signal processing (filter design, FFT, re-sampling, ...)
- ▶ Acoustic models
- ▶ Perceptual models

An exemplary application: Sound in 3D



Something about the company

- ▶ 5 employees
- ▶ Licensable technologies for pro, consumer, voice
- ▶ Custom technology adaptation/development
- ▶ Immersive Audio Processor

Website and other pointers

- ▶ <http://www.illusonic.com>

Quivid: automated audience measurement

Quivid provides qualified audience measurement using video analytics and off-the-shelf hardware:

- ▶ real-time processing of video streams
- ▶ data relayed to main data warehouse
- ▶ customers access formatted data remotely



Most metrics based on face detection/analysis:

- ▶ number of viewers, attention time, dwell time...
- ▶ gender, age estimation...
- ▶ footfall count via zenithal cameras

Quivid: audience data dashboards

Quivid | VIDICENTER v3

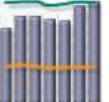
VidiCenter > Charts > Dashboards > Company ABC's audience dashboard

Company ABC's audience dashboard (administered by Quivid)

Over the last 30 days

Charts (UTC+1)

- 

Total viewers & avg Attention and Dwell Time
Last 30 Days (10 Jun 12 - 9 Jul 12)
Collapsed Data
Avg attention time: 2.2s
- 

Avg week: viewers, att. & dwell time
Last 30 Days (10 Jun 12 - 9 Jul 12)
Average Week growth vs previous period: -21.5%
Avg attention time: 2.2s
- 

Global attention time distribution
Last 30 Days (10 Jun 12 - 9 Jul 12)
Attention Time Distribution
1 location(s) - Aggregated
- 

Viewers per day
Last 30 Days (10 Jun 12 - 9 Jul 12)
Time Unit: Day
Total viewers: 129 858 persons
- 

Avg day: viewers, att. and dwell time
Last 30 Days (10 Jun 12 - 9 Jul 12)
Average Day Mean viewers per day: 2 190 persons
- 

Global dwell time distribution
Last 30 Days (10 Jun 12 - 9 Jul 12)
Dwell Time Distribution
1 location(s) - Aggregated
- 

Aver. Attention time by gender
Last 30 Days (10 Jun 12 - 9 Jul 12)
Collapsed Data
1 location(s) - Split by Location
- 

Aver. Attention time by age
Last 30 Days (10 Jun 12 - 9 Jul 12)
Collapsed Data
1 location(s) - Split by Location
- 

Gender split
Last 30 Days (10 Jun 12 - 9 Jul 12)
Collapsed Data
1 location(s) - Split by Location
- 

Age split
Last 30 Days (10 Jun 12 - 9 Jul 12)
Collapsed Data
1 location(s) - Split by Location

Actions

- Edit Dashboard
- Organize Charts
- Add a New Chart
- Multiple Chart Edit
- Duplicate Dashboard
- Delete Dashboard
- Clean Cache

Modules

- Charts Module
- Reports Module NEW
- Manager Module
- Playlists Module
- Help



P&G

Coca-Cola

P
Point Media US LLC

MICRODATA LIFERNEA

FIRMATODO

eimedio

ACCESS11
NET COMMUNICATIONS

Keystone

Alpha Pharm

McDonald's

7-Eleven

accenture

MITSUBISHI

CITROËN

Showbiz

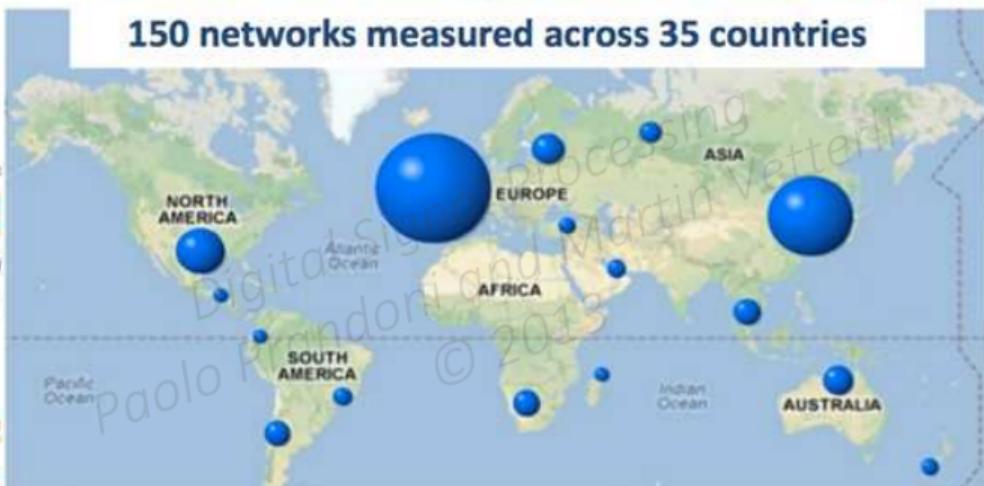
Imperial Tobacco

CHANGI
airport group

Zelia

MY
CO

TERRANOVA



<http://www.quividi.com>

What are the problems addressed?

- ▶ Environmental monitoring: real-time spatial visualization
- ▶ Precision agriculture: secure, control, and optimize crop production
- ▶ Sensor data management: access/control/share data anywhere/anytime

What tools used?

- ▶ Wireless sensor networks (WSN)
- ▶ Signal and image processing: sampling, compression, reconstruction...
- ▶ Radio communication

An exemplary application: environmental monitoring with sensor networks

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About the company

- ▶ 5 employees
- ▶ Main markets: environmental monitoring, precision agriculture
- ▶ Main product: DS3 system, flexible modules to easily compose a WSN

Website and other pointers

- ▶ <http://www.sensorscope.ch>
- ▶ <http://www.climaps.com>

Vidinoti is active in the field of Augmented Reality on mobile devices. More specifically, the main challenges are:

- ▶ Image recognition robust to environment changes (lighting, distortion, ...)
- ▶ Time and memory constraints to perform real-time image recognition and tracking on mobile devices
- ▶ Load balancing between remote server, containing a large amount of images to recognize, and mobile devices

To tackle these challenges, Vidinoti uses:

- ▶ Advanced image recognition algorithms
- ▶ Objects tracking taking advantage of sensors and image data
- ▶ Algorithm optimization tailored to mobile devices

Vidinoti technology is cloud-based, providing a seamless integration of all Augmented Reality components to customers.



Vidinoti started in 2010 as a spin-off of the LCAV, now in Fribourg (CH).
The company currently employs about 10 people having the missions of:

- ▶ Business development
- ▶ Research and development
- ▶ IP watch, investigation and creation

Vidinoti objective is to allow customers to deliver additional multimedia content to their end-users using Augmented Reality, in markets such as:

- ▶ Marketing, Printed media, Museums

For more information, please visit Vidinoti website and try the iPhone app, PixLive, using Vidinoti technology:

- ▶ <http://www.vidinoti.com>
- ▶ <http://www.pixlive.info>

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Module 10.4: Acknowledgements

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- ▶ Juri Ranieri

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- ▶ Tao Lee

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- ▶ Youssef El Baba
- ▶ Taher Nguira
- ▶ Solene Buet

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- ▶ Andrea Ridolfi
- ▶ Lionel Coulot

Homework Sets:

- ▶ Juri Ranieri
 - ▶ Yann Barbotin
 - ▶ Ivan Dokmanic
 - ▶ Zhou Xue
 - ▶ Reza Parhizkar
 - ▶ Feng Yang
 - ▶ Mihailo Kolundzija
 - ▶ Mitra Fatemi
 - ▶ Dirk Schroder
 - ▶ Andreas Walther
 - ▶ Alireza Ghasemi
 - ▶ Marta Martinez-Camara
 - ▶ Zichong Chen
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- ▶ Jacqueline Aeberhard

Funding:

- ▶ EPFL

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