A sparse equivalent source method for near-field acoustic holography

This study examines a near-field acoustic holography method consisting of a sparse formulation of the equivalent source method, based on the compressive sensing (CS) framework. The method, denoted Compressive–Equivalent Source Method (C-ESM), encourages spatially sparse solutions (based on the superposition of few waves) that are accurate when the acoustic sources are spatially localized. The importance of obtaining a non-redundant representation, i.e., a sensing matrix with low column coherence, and the inherent ill-conditioning of near-field reconstruction problems is addressed. Numerical and experimental results on a classical guitar and on a highly reactive dipolelike source are presented. C-ESM is valid beyond the conventional sampling limits, making wideband reconstruction possible. Spatially extended sources can also be addressed with C-ESM, although in this case the obtained solution does not recover the spatial extent of the source.
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Original language: English
Direction-of-arrival (DOA) estimation refers to the localization of sound sources on an angular grid from noisy measurements of the associated wavefield with an array of sensors. For accurate localization, the number of angular look-directions is much larger than the number of sensors, hence, the problem is underdetermined and requires regularization. Traditional methods use an L2-norm regularizer, which promotes minimum-power (smooth) solutions, while regularizing with L1-norm promotes sparsity. Sparse signal reconstruction improves the resolution in DOA estimation in the presence of a few point sources, but cannot capture spatially extended sources. The DOA estimation problem is formulated in a Bayesian framework where regularization is imposed through prior information on the source spatial distribution which is then reconstructed as the maximum a posteriori estimate. A composite prior is introduced, which simultaneously promotes a piecewise constant profile and sparsity in the solution. Simulations and experimental measurements show that this choice of regularization provides high-resolution DOA estimation in a general framework, i.e., in the presence of spatially extended sources.
Compressive sensing with a spherical microphone array

A wave expansion method is proposed in this work, based on measurements with a spherical microphone array, and formulated in the framework provided by Compressive Sensing. The method promotes sparse solutions via ‘1-norm minimization, so that the measured data are represented by few basis functions. This results in fine spatial resolution and accuracy. This publication covers the theoretical background of the method, including experimental results that illustrate some of the fundamental differences with the "conventional" leastsquares approach. The proposed methodology is relevant for source localization, sound field reconstruction, and sound field analysis.

General information
State: Published
Organisations: Department of Electrical Engineering, Acoustic Technology, Department of Applied Mathematics and Computer Science
Authors: Fernandez Grande, E. (Intern), Xenaki, A. (Intern)
Number of pages: 5
Publication date: 2016
Main Research Area: Technical/natural sciences
Multisnapshot Sparse Bayesian Learning for DOA

The directions of arrival (DOA) of plane waves are estimated from multisnapshot sensor array data using sparse Bayesian learning (SBL). The prior for the source amplitudes is assumed independent zero-mean complex Gaussian distributed with hyperparameters, the unknown variances (i.e., the source powers). For a complex Gaussian likelihood with hyperparameter, the unknown noise variance, the corresponding Gaussian posterior distribution is derived. The hyperparameters are automatically selected by maximizing the evidence and promoting sparse DOA estimates. The SBL scheme for DOA estimation is discussed and evaluated competitively against LASSO (l(1)-regularization), conventional beamforming, and MUSIC.
Grid-free compressive beamforming
The direction-of-arrival (DOA) estimation problem involves the localization of a few sources from a limited number of observations on an array of sensors, thus it can be formulated as a sparse signal reconstruction problem and solved efficiently with compressive sensing (CS) to achieve high-resolution imaging. On a discrete angular grid, the CS reconstruction degrades due to basis mis-match when the DOAs do not coincide with the angular directions on the grid. To overcome this limitation, a continuous formulation of the DOA problem is employed and an optimization procedure is introduced, which promotes sparsity on a continuous optimization variable. The DOA estimation problem with infinitely many unknowns, i.e., source locations and amplitudes, is solved over a few optimization variables with semidefinite programming. The grid-free CS reconstruction provides high-resolution imaging even with non-uniform arrays, single-snapshot data and under noisy conditions as demonstrated on experimental towed array data.
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Original language: English

Electronic versions:

JAS_vol_137_iss_4_1923_1.pdf. Embargo ended: 01/10/2015
High-resolution imaging methods in array signal processing
The purpose of this study is to develop methods in array signal processing which achieve accurate signal reconstruction from limited observations resulting in high-resolution imaging. The focus is on underwater acoustic applications and sonar signal processing both in active (transmit and receive) and passive (only receive) mode. The study addresses the limitations of existing methods and shows that, in many cases, the proposed methods overcome these limitations and outperform traditional methods for acoustic imaging.

The project comprises two parts; The first part deals with computational methods in active sonar signal processing for detection and imaging of submerged oil contamination in sea water from a deep-water oil leak. The submerged oil field is modeled as a uid medium exhibiting spatial perturbations in the acoustic parameters from their mean ambient values which cause weak scattering of the incident acoustic energy. A highfrequency active sonar is selected to insonify the medium and receive the backscattered waves. High-frequency acoustic methods can both overcome the optical opacity of water (unlike methods based on electromagnetic waves) and resolve the small-scale structure of the submerged oil field (unlike low-frequency acoustic methods). The study shows that high-frequency acoustic methods are suitable not only for large-scale localization of the oil contamination in the water column but also for statistical characterization of the submerged oil field through inference of the spatial covariance of its acoustic parameters.

The second part of the project investigates methods that exploit sparsity in order to achieve super-resolution in sound source localization with passive sonars. Sound source localization with sensor arrays involves the estimation of the direction-of-arrival (DOA) of the associated wavefronts from a limited number of observations. Usually, there are only a few sources generating the acoustic wavefield such that DOA estimation is essentially a sparse signal reconstruction problem. Conventional methods for DOA estimation (i.e., beamforming) suffer from resolution limitations related to the physical size and the geometry of the array. DOA estimation methods that are developed up-to-date in order to overcome the resolution limitations of conventional methods involve the estimation or the eigendecomposition of the data cross-spectral matrix. The cross-spectral methods require many snapshots (i.e., observation windows of the recorded wavefield) hence are suitable only for stationary incoherent sources. In this study, the DOA estimation problem is formulated both for single and multiple snapshots in the compressive sensing framework (CS), which achieves sparsity, thus improved resolution, and can be solved efficiently with convex optimization. It is shown that CS has superior performance compared to traditional DOA estimation methods especially under challenging scenarios such as coherent arrivals, single-snapshot data and random array configurations. The high-resolution performance and the robustness of CS in DOA estimation are validated with experimental array data from ocean acoustic measurements.

Multiple and single snapshot compressive beamforming
For a sound field observed on a sensor array, compressive sensing (CS) reconstructs the direction of arrival (DOA) of multiple sources using a sparsity constraint. The DOA estimation is posed as an underdetermined problem by expressing the acoustic pressure at each sensor as a phase-lagged superposition of source amplitudes at all hypothetical DOAs. Regularizing with an 1-norm constraint renders the problem solvable with convex optimization, and promoting sparsity gives high-resolution DOA maps. Here the sparse source distribution is derived using maximum a posteriori estimates for both single and multiple snapshots. CS does not require inversion of the data covariance matrix and thus works well even
for a single snapshot where it gives higher resolution than conventional beamforming. For multiple snapshots, CS outperforms conventional high-resolution methods even with coherent arrivals and at low signal-to-noise ratio. The superior resolution of CS is demonstrated with vertical array data from the SWellEx96 experiment for coherent multi-paths.

**General information**
- State: Published
- Organisations: Center for Energy Resources Engineering, Department of Applied Mathematics and Computer Science, Scientific Computing, Acoustic Technology, Technische Universität Wien, University of California, San Diego
- Authors: Gerstoft, P. (Ekstern), Xenaki, A. (Intern), Mecklenbrauker, C. F. (Ekstern)
- Pages: 2003–2014
- Publication date: 2015
- Main Research Area: Technical/natural sciences

**Publication information**
- Journal: Journal of the Acoustical Society of America
- Volume: 138
- Issue number: 4
- ISSN (Print): 0001-4966
- Ratings:
  - BFI (2018): BFI-level 2
  - Web of Science (2018): Indexed yes
  - BFI (2017): BFI-level 2
  - Web of Science (2017): Indexed yes
  - BFI (2016): BFI-level 2
  - Scopus rating (2016): CiteScore 1.83 SJR 0.749 SNIP 1.27
  - Web of Science (2016): Indexed yes
  - BFI (2015): BFI-level 2
  - Scopus rating (2015): SJR 0.802 SNIP 1.437 CiteScore 1.77
  - Web of Science (2015): Indexed yes
  - BFI (2014): BFI-level 2
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  - Web of Science (2014): Indexed yes
  - BFI (2013): BFI-level 2
  - Scopus rating (2013): SJR 0.705 SNIP 1.966 CiteScore 2
  - ISI indexed (2013): ISI indexed yes
  - Web of Science (2013): Indexed yes
  - BFI (2012): BFI-level 2
  - Scopus rating (2012): SJR 0.763 SNIP 1.622 CiteScore 1.75
  - ISI indexed (2012): ISI indexed yes
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  - Scopus rating (2006): SJR 0.752 SNIP 1.559
  - Web of Science (2006): Indexed yes
Multiple snapshot compressive beamforming

For sound fields observed on an array, compressive sensing (CS) reconstructs the multiple source signals at unknown directions-of-arrival (DOAs) using a sparsity constraint. The DOA estimation is posed as an underdetermined problem expressing the field at each sensor as a phase-lagged superposition of source amplitudes at all hypothetical DOAs. CS is applicable even for a single observation snapshot achieving a higher resolution than conventional beamforming. For multiple snapshots, CS outperforms conventional high-resolution methods, even with coherent arrivals and at low signal-to-noise ratio.

Sparse acoustic imaging with a spherical array

In recent years, a number of methods for sound source localization and sound field reconstruction with spherical microphone arrays have been proposed. These arrays have properties that are potentially very useful, e.g. omnidirectionality, robustness, compensable scattering, etc. This paper proposes a plane wave expansion method based on measurements with a spherical microphone array, and solved in the framework provided by Compressed Sensing. The proposed methodology results in a sparse solution, i.e. few non-zero coefficients, and it is suitable for both source localization and sound field reconstruction. In general it provides fine spatial resolution for localization (delta-like functions), and robust reconstruction (the noisy components are naturally suppressed). The validity and performance of the proposed method is examined, and its limitations as well as the underlying assumptions are addressed.
Sparse DOA estimation with polynomial rooting

Direction-of-arrival (DOA) estimation involves the localization of a few sources from a limited number of observations on an array of sensors. Thus, DOA estimation can be formulated as a sparse signal reconstruction problem and solved efficiently with compressive sensing (CS) to achieve high-resolution imaging. Utilizing the dual optimal variables of the CS optimization problem, it is shown with Monte Carlo simulations that the DOAs are accurately reconstructed through polynomial rooting (Root-CS). Polynomial rooting is known to improve the resolution in several other DOA estimation methods. However, traditional methods involve the estimation of the cross-spectral matrix hence they require many snapshots and stationary incoherent sources and are suitable only for uniform linear arrays (ULA). Root-CS does not have these limitations as demonstrated on experimental towed array data from ocean acoustic measurements.

The equivalent source method as a sparse signal reconstruction

This study proposes an acoustic holography method for sound field reconstruction based on a point source model, which uses the Compressed Sensing (CS) framework to provide a sparse solution. Sparsity implies that the sound field can be represented by a minimal number of non-zero terms, point sources in the case of this model. Sparse solutions can be achieved by l-1 norm minimization, providing accurate reconstruction and robustness to noise, because favouring sparsity suppresses noisy components. The study addresses the influence of the ill-conditioning of the propagation matrix, which can be a challenge for inverse problems where the energy in the solution vector is much greater than the energy in the observations (particularly in acoustic near-fields). Finally, the study examines the case of spatially extended sources and problems where the sparsity condition is not certainly guaranteed.
Compressive beamforming

Sound source localization with sensor arrays involves the estimation of the direction-of-arrival (DOA) from a limited number of observations. Compressive sensing (CS) solves such underdetermined problems achieving sparsity, thus improved resolution, and can be solved efficiently with convex optimization. The DOA estimation problem is formulated in the CS framework and it is shown that CS has superior performance compared to traditional DOA estimation methods especially under challenging scenarios such as coherent arrivals and single-snapshot data. An offset and resolution analysis is performed to indicate the limitations of CS. It is shown that the limitations are related to the beampattern, thus can be predicted. The high-resolution capabilities and the robustness of CS are demonstrated on experimental array data from ocean acoustic measurements for source tracking with single-snapshot data.
Sparsity and super-resolution in sound source localization with sensor arrays

Sound source localization with sensor arrays involves the estimation of the direction-of-arrival (DOA) from a limited number of observations. Compressive sensing (CS) is a method for solving such underdetermined problems which achieves simultaneously sparsity, thus super-resolution, and computational speed. We formulate the DOA estimation as a sparse signal reconstruction problem and show that methods which exploit sparsity have superior performance compared to traditional methods for DOA estimation. To demonstrate the high-resolution capabilities and the robustness of CS and other sparsity promoting optimization techniques in DOA estimation, the methods are applied to experimental data from underwater acoustic measurements in the challenging scenario of source tracking from single snapshot data.

General information
State: Published
Organisations: Department of Applied Mathematics and Computer Science, University of California, San Diego
Authors: Xenaki, A. (Intern), Gerstoft, P. (Ekstern), Mosegaard, K. (Intern)
Number of pages: 6
Pages: 783-788
Publication date: 2014

Host publication information
Title of host publication: Proceedings - 2nd Underwater Acoustics Conference and Exhibition
Editors: Papadakis, J. S., Bjørnø, L.
ISBN (Electronic): 978-618-80725-1-0
Main Research Area: Technical/natural sciences
Conference: 2nd international conference and exhibition on Underwater Acoustics, Rhodos, Greece, 22/06/2014 - 22/06/2014
Inversion assuming weak scattering
The study of weak scattering from inhomogeneous media or interface roughness has long been of interest in sonar applications. In an acoustic backscattering model of a stationary field of volume inhomogeneities, a stochastic description of the field is more useful than a deterministic description due to the complex nature of the field. A method based on linear inversion is employed to infer information about the statistical properties of the scattering field from the obtained cross-spectral matrix. A synthetic example based on an active high-frequency sonar demonstrates that the proposed method provides a quantitative description of a weak scattering field in terms of its second-order statistics.

General information
State: Published
Organisations: Department of Applied Mathematics and Computer Science, Center for Energy Resources Engineering, University of California
Authors: Xenaki, A. (Intern), Gerstoft, P. (Ekstern), Mosegaard, K. (Intern)
Number of pages: 6
Publication date: 2013

Modeling and detection of oil in sea water
The challenge of a deep-water oil leak is that a significant quantity of oil remains in the water column and possibly changes properties. There is a need to quantify the oil settled within the water column and determine its physical properties to assist in the oil recovery. There are currently no methods to map acoustically submerged oil in the sea. In this paper, high-frequency acoustic methods are proposed to localize the oil polluted area and characterize the parameters of its spatial covariance, i.e., variance and correlation. A model is implemented to study the underlying mechanisms of backscattering due to spatial heterogeneity of the medium and predict backscattering returns. An algorithm for synthetically generating stationary, Gaussian random fields is introduced which provides great flexibility in implementing the physical model of an inhomogeneous field with spatial covariance. A method for inference of spatial covariance parameters is proposed to describe the scattering field in terms of its second-order statistics from the backscattered returns. The results indicate that high-frequency acoustic methods not only are suitable for large-scale detection of oil contamination in the water column but also allow inference of the spatial covariance parameters resulting in a statistical description of the oil field.

General information
State: Published
Organisations: Department of Applied Mathematics and Computer Science, National Space Institute, Mathematical and Computational Geoscience, University of California, San Diego
Authors: Xenaki, A. (Intern), Gerstoft, P. (Ekstern), Mosegaard, K. (Intern)
Number of pages: 9
Pages: 2790-2798
Publication date: 2013
Main Research Area: Technical/natural sciences
Ratings:

BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 1.83 SJR 0.749 SNIP 1.27
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): SJR 0.802 SNIP 1.437 CiteScore 1.77
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): SJR 0.788 SNIP 1.423 CiteScore 1.8
Web of Science (2014): Indexed yes
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Scopus rating (2013): SJR 0.705 SNIP 1.966 CiteScore 2
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): SJR 0.763 SNIP 1.622 CiteScore 1.75
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): SJR 0.695 SNIP 1.642 CiteScore 1.68
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 0.754 SNIP 1.528
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BFI (2009): BFI-level 2
Scopus rating (2009): SJR 0.783 SNIP 1.717
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Scopus rating (2008): SJR 0.848 SNIP 1.633
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Scopus rating (2007): SJR 0.865 SNIP 1.647
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Scopus rating (2006): SJR 0.752 SNIP 1.559
Web of Science (2006): Indexed yes
Scopus rating (2005): SJR 0.954 SNIP 1.749
Web of Science (2005): Indexed yes
Scopus rating (2004): SJR 0.77 SNIP 1.787
Web of Science (2004): Indexed yes
Scopus rating (2003): SJR 0.882 SNIP 1.712
Web of Science (2003): Indexed yes
Scopus rating (2002): SJR 0.87 SNIP 1.501
Web of Science (2002): Indexed yes
Scopus rating (2001): SJR 0.719 SNIP 1.467
Web of Science (2001): Indexed yes
Scopus rating (2000): SJR 0.621 SNIP 1.411
Web of Science (2000): Indexed yes
Scopus rating (1999): SJR 0.591 SNIP 1.319

Original language: English

DOIs:
Statistical characterization of weak scattering fields with inverse methods
In an acoustic backscattering model of a stationary field of volume inhomogeneities, a stochastic description of the field is more useful than a deterministic description due to the complex nature of the field. A method based on linear inversion is developed to infer information about the statistical properties of the scattering field from the obtained cross-spectral matrix.

General information
State: Published
Organisations: Department of Applied Mathematics and Computer Science, Mathematical and Computational Geoscience, University of California, San Diego
Authors: Xenaki, A. (Intern), Gerstoft, P. (Ekstern), Carriere, O. (Ekstern), Mosegaard, K. (Intern)
Number of pages: 7
Publication date: 2013

Host publication information
Title of host publication: MTS/IEEE Oceans '13
Publisher: IEEE
Main Research Area: Technical/natural sciences

Bibliographical note
MTS/IEEE Oceans 2013
Source: dtu
Source-ID: u::9056
Publication: Research - peer-review › Article in proceedings – Annual report year: 2013

Improving the resolution of three-dimensional acoustic imaging with planar phased arrays
This paper examines and compares two methods of improving the quality of three-dimensional beamforming with phased microphone arrays. The intended application is the detection of aerodynamic noise sources on wind turbines. Both methods employ Fourier based deconvolution. The first method involves a transformation of coordinates that tends to make the response to a point source, the point spread function, more shift invariant. The result is a significant improvement in sound source imaging in the transformed coordinate system. However, the inverse transformation to Cartesian coordinates introduces range dependent resolution limitations because of the irregular distribution of the focal points. The second method combines the transformation of coordinates with an alternative scanning technique. This method can be used in near field three-dimensional acoustic imaging to produce maps free of sidelobes and with constant resolution. The robustness of the proposed methods is validated both with computer simulations and experimentally.

General information
State: Published
Organisations: Department of Electrical Engineering, Acoustic Technology
Authors: Xenaki, A. (Intern), Jacobsen, F. (Intern), Fernandez Grande, E. (Intern)
Pages: 1939-1950
Publication date: 2012
Main Research Area: Technical/natural sciences

Publication information
Journal: Journal of Sound and Vibration
Volume: 331
Issue number: 8
ISSN (Print): 0022-460X
Ratings:
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.09 SJR 1.462 SNIP 2.162
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Improving the resolution of beamforming measurements on wind turbines

The spatial resolution of a beamformer based on a planar microphone array in a measurement plane parallel to the array can be approximated by a two-dimensional convolution of the actual distribution of incoherent sources and the
beamformer’s response to a point source. Several methods are available for deconvolving the resulting blurred picture and thus improving the resulting resolution. This investigation is concerned with a similar deconvolution for the three-dimensional case.

General information
State: Published
Organisations: Acoustic Technology, Department of Electrical Engineering
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Publication date: 2010

Host publication information
Title of host publication: Proceedings of 20th International Congress on Acoustics
Main Research Area: Technical/natural sciences
Links:
Source: orbit
Source-ID: 282649
Publication: Research - peer-review › Article in proceedings – Annual report year: 2010

Projects:
Computational methods for detection and imaging of oil in sea water
Technical University of Denmark
Period: 01/07/2011 → 13/08/2015
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Financing sources
Source: Internal funding (public)
Name of research programme: 1/3 FUU, 1/3 inst 1/3 Andet
Project: PhD