SENSOR ARRAY SIGNAL PROCESSING

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Prologue

An array of sensors is often used in many diverse fields of science and engineering, particularly where the goal is to study propagating wavefields. Some examples are astronomy (radio astronomy), medical diagnosis, radar, communication, sonar, nonrestrictive testing, seismology, and seismic exploration (see [1] for different applications of the array signal processing). The main goal of array signal processing is to deduce the following information through an analysis of wavefields:

- (a) Source localization as in radar, sonar, astronomy, and seismology, etc.
- (b) Source waveform estimation as in communication, etc.
- (c) Source characterization as in seismology
- (d) Imaging of the scattering medium as in medical diagnosis, seismic exploration, etc.

The tools of array signal processing remain the same, cutting across the boundaries of different disciplines. For example, the basic tool of beamformation is used in many areas mentioned above. The present book aims at unraveling the underlying basic principles of array signal processing without a reference to any particular application. However, an attempt is made to include as many tools as possible from different disciplines in an order which reflects the underlying principle.

In the real world, different types of wavefields are used in different applications, for example, acoustic waves in sonar, mechanical waves in seismic exploration, electromagnetic waves in radar and radio astronomy. Fortunately, all wavefields can be characterized under identical mathematical framework. This common mathematical framework is briefly summarized in chapter 1. Here we have described the basic equations underlying different wavefields and the structure of array signals and the background noise when the noise sources follow some simple geometrical distribution. The topics covered are wavefield in open space, bounded space including multipath propagation and layered medium. Also covered is the weak scattering phenomenon which is the basis for tomographic imaging. In chapter 2 we study different types of sensor configurations. The emphasis is however on commonly used uniform linear array (ULA), uniform circular array (UCA). Many practical sensor array systems can be studied in terms of the basic ULA and UCA systems (cylindrical array in radar and sonar, cross array in astronomy and seismology). Like sensors, the sources can also be configured in the form of an array. The source array is useful in synthesizing a desired wavefront and/or waveform. In chapter 3 we examine the issues connected with the design of 2D digital filters for wavefield analysis. Since the propagating wavefields possess some interesting spectral characteristics in frequency wavenumber domain, for example, the spectrum of a propagating wavefront is always on a radial line, it is natural to take into account these features in the design of digital filters for separation of interfering wavefields. Specifically, we cover in detail the design of a fan filter and quadrant filter. Also, the classical Wiener filter as an optimum least squares filter is covered in this chapter.

The theme in chapters 4 and 5 is localization of a source. In chapter 4 we describe the classical methods based on the frequency wavenumber spectrum of the observed array output. We start with the Blackman Tukey type frequency wavenumber spectrum and then go on to modern nonlinear high resolution spectrum analysis methods such as Capon's maximum likelihood spectrum which is also known as minimum variance distortionless response (MVDR) beamformer and maximum entropy spectrum. Localization essentially involves estimation of parameters pertaining to the source position, for example, azimuth and elevation angles, range, speed if the source is moving, etc. In the last two decades a host of new methods of source localization have been invented. We elaborate these new approaches in chapter 5. These include subspace based methods, use of man-made signals such as in communication and finally multipath environment. Quite often localization must be done in the real time and it may be necessary to track a moving source. Adaptive techniques are best suited for such tasks. A brief discussion on adaptive approach is included. In chapter 6 we look into methods for source waveform separation and estimation. The direction of arrival (DOA) is assumed to be known or has been estimated. We shall describe a Wiener filter which minimizes the mean square error in the estimation of the desired signal coming from a known direction and a Capon filter which, while minimizing the power, ensures that the desired signal is not distorted. We also talk about the estimation of direction of arrival in a multipath environment encountered in wireless communication.

The next two chapters are devoted to array processing for imaging purposes. Firstly, in chapter 7 we look at different types of tomographic imaging systems: nondiffracting, diffracting and reflection tomography. The received wavefield is inverted under the assumption of weak scattering to map any one or more physical properties of the medium, for example, sound speed variations in a medium. For objects of regular shape, scattering points play an important role in geometrical diffraction theory. Estimation of these scattering points for the determination of shape is also discussed. In chapter 8 we study the method of wavefield extrapolation for imaging, extensively used in seismic exploration. The raw seismic traces are stacked in order to produce an output trace from a hypothetical sensor kept close to the source (with zero- offset). A suite of such stacked traces may be modeled as a wavefield recorded in an imaginary experiment wherein small charges are placed on the reflector and exploded at the same time. The zero-offset wavefield is used for imaging of reflectors. The imaging process may be looked upon as a downward continuation of the wavefield or inverse source problem or propagation backward in time, i.e., depropagation to the reflector. All three view points are very briefly described.

The book is based on a course entitled "Digital Array Processing" offered to the graduate students who had already taken a course on digital signal processing (DSP) and a course on modern spectrum analysis (MSA). It has been my conviction that a student should be exposed to all basic concepts cutting across the different disciplines without being burdened with the questions of practical applications which are usually dealt with in specialty courses. The most satisfying experience is that there is a common thread that connects seemingly different tools used in different disciplines. An example is beamformation, a commonly used tool in radar/sonar, which has a close similarity with stacking used in seismic exploration. I have tried to bring out in this exposition the common thread that exists in the analysis of wavefields used in a wide variety of application areas. The proposed book has a significantly different flavor, both in coverage and depth in comparison with the ones on the market [1-5]. The first book, edited by Haykin, is a collection of chapters, each devoted to an application. It rapidly surveys the state of art in respective application areas but does not go deep enough and describe the basic mathematical theory required for the understanding of array processing. The second book by Ziomek is entirely devoted to array signal processing in underwater acoustics. It covers in great depth the topic of beamformation by linear and planar arrays but confines to linear methods. Modern array processing tools do not find a place in this book. The third book by Pillai [3] has a very narrow scope as it deals with in great detail only the subspace based methods. The fourth book by Bouvet and Bienvenu (Eds) is again a collection of papers largely devoted to modern subspace techniques. It is not suitable as a text. Finally, the present book has some similarities with a book by Johnson and Dudgeon [3] but differs in one important respect, namely, it does not cover the application of arrays to imaging though a brief mention of tomography is made. Also, the present book covers newer material which was not available at the time of the publication of the book by Johnson and Dudgeon. During the last two decades there has been intense research activity in the area of array signal processing. There have been at least two review papers summarizing the new results obtained during this period. The present book is not a research monograph but it is an advanced level text which focuses on the important developments which, the author believes, should be taught to give a broad "picture" of array signal processing.

I have adopted the following plan of teaching. As the entire book cannot be covered in one semester (about 35 hours) I preferred to cover it in two parts in alternate semesters. In the first part, I covered chapter 1 (exclude §1.6), chapter 2, chapters 4, 5 and 6. In the second part, I covered chapter 1, chapter 2 (exclude §2.3), chapter 3 (exclude §3.5), chapters 7 and 8. Exercises are given at the end of each chapter. (The solution guide may be obtained from the publisher).

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Dedication

This work is dedicated to the memory of the great visionary , J. R. D Tata who shaped the Indian Institute of Science for many decades.