A MATLAB TOOLBOX FOR RADAR ARRAY PROCESSING

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ABSTRACT

This paper describes the design, implemented possibilities and usage of a MATLAB Toolbox for radar signal processing. The Toolbox is especially suited for processing in the spatial dimension using signals from an antenna array. Both simulated and measured signals can be used. Both conventional processing, e.g. conventional beamforming, and model based processing is possible.

1. INTRODUCTION

A MATLAB toolbox called DBT for narrowband radar array processing is under development at FOA. By radar array processing we mean signal processing in the spatial dimension in a radar using signals from an antenna array. MATLAB is a well-known programmable software for numerical computations and data visualization.

The objectives of DBT are to help us in the research on radar array processing, to perform array processing on measured radar signals, to support cooperation in development of software tools and to serve as a software demonstrator.

2. RADAR SIGNALS

The purpose of surveillance and tracking radars is basically to detect targets, estimate the direction to targets and estimate range and velocity of targets in a hostile signal background, which can be both natural and man-made. This is done by transmitting an RF signal that is pulsed in time with a certain PRF (pulse repetition frequency) and has a certain waveform (figure 1). The signal from target echoes (figure 2) is received with a receiver antenna and converted to a digital complex baseband signal.

Figure 1: Transmitted signal.

Received time snapshots from the same pulse (figure 2) represent different range samples. Time snapshots from different pulses represent different time samples (pulses) from the same ranges. This, together with the signals from different channels of a digital array antenna, form a multidimensional radar signal, a radar datacube (figure 3, left).

Figure 2: Received signal (active mode).

Figure 3: A radar signal as a radar datacube before (left) and after (right) conventional processing.

3. THE FOA EXPERIMENTAL ANTENNA

At FOA, an experimental S-band receiving digital array antenna for radar applications has been designed and built [1]. The experimental antenna consists of a linear array of 12 antenna elements, receiver modules, A/D converters and buffer memories. The antenna has an agile frequency band of 2.8-3.3 GHz and an instantaneous bandwidth of 5 MHz. I/Q-conversion, down conversion and equalizing are done in non-real time in a standard computer. The recorded signals can then be transferred to DBT.

4. DESIGN AND IMPLEMENTATION

4.1 Representation of Received Signals

The received radar signal is represented by its complex envelope and is stored in the radar datacube as a MATLAB multidimensional matrix. Before any processing is done, the indices of the radar datacube (figure 3, left) are: (pulseix, timelnPulseix, channelix, exteix, ...
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cp indexed, trial indexed), where pulse indexed is the index of the received pulses (figure 2), time in pulse indexed is the index of received time snapshots within one pulse, channel indexed is the index of the antenna channels, extra indexed is an user defined index, cpi indexed is the index of the CPIs (Coherent Processing Intervals) and trial indexed is the index of repeated trials.

In this paper, the term "conventional processing" means linear filtering in the form of conventional beamforming, Doppler filtering and pulse compression (figure 4). After conventional processing, the indices must be interpreted differently. If no data reduction is done, the information in the radar datacube should be the same as before. We have only made a change of basis in a vector space to make it easier to see the relevant information. What is stored in the radar datacube, are the coordinates in a specific basis. For example, when performing doppler filtering, we change from the trivial basis \( \delta (t, \pm T) \) (different \( T \)s) to the Fourier basis \( e^{jk \omega t} \) (different \( \omega \)s).

Conventional Processing

Indices after complete conventional processing (figure 3, right) are (dopplerChan indexed, rangeBin indexed, beam indexed, extra indexed, cpi indexed, trial indexed), where dopplerChan indexed is the index of Doppler channels, rangeBin indexed is the index of range bins and beam indexed is the index of formed beams.

Before or after conventional processing, model based detection and estimation methods can be used to estimate, for example, the number of targets, direction to and doppler and range of targets (figure 4). The direction to targets are expressed by the direction-of-arrival (DOA) of the reflected signals.

4.2 Current Implementation (Release 2.13)

At present, only one angle (azimuth or elevation) of the DOA of sources can be used in DBT but DBT is prepared for the second angle. Spatial signal processing requires an array antenna but the other parts of the toolbox can be used also for single-channel antennas. The methods for spatial signal processing are independent of the used receiver antenna since the model for the receiver antenna is localized to the function that calculates spatial steering vectors.

The following is implemented in the present release (2.13):

- Modeling of array antennas with and without beamforming to subarrays. The antenna elements can be placed arbitrarily and have arbitrary element patterns.
- Antenna pattern plots with specified tapering, main beam direction, adaptive sidelobe cancellation and model errors (figure 5).
- Simulation of model errors: antenna element positions, antenna element patterns, broken antenna elements and amplitude, phase and I/Q-errors in the channels.
- Single range simulation of gaussian random narrowband signals with arbitrary source correlation matrix.
- Single range simulation of wideband signals with a gaussian distribution or a specified time signal.
- Simulation of narrowband radar signals with specified doppler shifts and waveform (rectangular pulse, Barker, Frank and Chirp code, measured or user defined).
- Simulation of gaussian distributed noise with arbitrary spatial correlation matrix.
- Simulation of exponentially distributed clutter (fig. 6).
- Pulse compression with any of the waveforms above.
- Connection to the FOA experimental antenna: Acquisition of signals, near-field compensation and five methods for calibration compensation.
- Conventional beamforming with beamforming weights according to five basic methods. Tapering (uniform, Taylor, Chebychev and user defined), adaptive sidelobe cancellation and beam orthogonalization are possible.
- Doppler filtering by FFT.
- Spectral DOA estimation [2]: conventional beamformer, Capon, MUSIC, Min-norm. (Figure 7, 8 and 9)
- Parametric DOA estimation [2]: Stochastic Maximum

![Figure 5: Antenna pattern, both unadapted and adapted to jammers at DOA 40° and 60°.](image-url)

- Simulation of model errors: antenna element positions, antenna element patterns, broken antenna elements and amplitude, phase and I/Q-errors in the channels.
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Figure 6: Simulated radar and clutter signal after pulse compression and conventional beamforming. There are three targets at DOA \(-3^\circ, 18^\circ\) and \(25^\circ\).

Figure 7: Result of DOA estimation with 25 overlapping subarrays with three elements each. Subarray spacing is one wavelength. Note the grating lobes for both conventional beamforming and MUSIC.

- Likelihood (SML), Deterministic Maximum Likelihood (DML), Parametric Target Model Fitting (PTMF), Weighted Subspace Fitting (WSF), Subspace Fitting (SSF), ESPRIT, Root MUSIC and four methods for the estimation of DOAs from DOA spectra.
- Calculation of theoretic performance bounds of DOA estimates by the Cramér Rao Bound.
- Estimation and modification of the spatial correlation matrix from arbitrary snapshots with Maximum Likelihood, Forward-backward averaging, Spatial smoothing [2] and Diagonal loading.
- Estimation of the number of sources from spatial information with AIC, MDL and the estimation of the number of peaks in DOA spectra with four methods.

Figure 8: Measured radar signal after MUSIC spectrum estimation on each range bin separately.

- Estimation of the instantaneous frequency of a signal and the noise power.
- Plot of received signals, spatial correlation matrices, eigenvalues of correlation matrices and DOA spectra.

4.3 Development of DBT

To manage the software version and release control of the currently about 26000 lines of code and help text in a multi-developer environment, we use the CVS source code version management system [3].

Ongoing and planned development of DBT is:

- Model based signal processing in Doppler and range.
- Clutter simulation with moving radar, targets, jammers.
- STAP (Space Time Adaptive Processing).
- Use of a full spherical coordinate system with two angles (azimuth and elevation) for DOAs.
- A demonstrator of radar array processing with a graphical user interface.
- Conversion of the program structure to object orientation to facilitate the maintenance and software quality.

5. HOW TO USE THE TOOLBOX

5.1 An Extended MATLAB Language

DBT is an extension of the MATLAB programming language with data types and functions for signal processing in radar, especially antenna array processing. This constitutes a language on a higher level than standard MATLAB, a language that is specially suited for its purpose. The toolbox is extendible by the users. The internal interfaces, mostly MATLAB structure variables [4], are standardized [5].
5.2 Sequence of Commands

A typical main program using DBT has the following sequence of commands, some of which can be omitted.

1. Definition of receiver antenna.
2. Acquire a signal, simulated or measured.
3. Calibration compensation of signal or set the compensation method to be used by steering vector compensation.
4. Conventional processing. Several steps can be made with a radar datacube (see figure 4).
5. Select data for model based processing.
6. Estimate and modify a spatial correlation matrix. Several steps can be made with a correlation matrix.
7. Model based detection and estimation.
8. Present the result.

For statistical analysis, surround points 2) to 7) by a normal MATLAB loop (for ... end).

An example program with a circular array antenna with a radius of half a wavelength and with eight omni-directional elements is shown below. The graph created by the program are shown in figure 9.

% Definition of constants. Create elements and calculate element positions:
% Create the array:
ant2 = defant('array', elemPos, [], elem2);
% Generate simulated received antenna signals:
sig = compsim(ant2, lambda, 100, 'rndnw', ...
[theta, phi, SNR, alpha, dalpha, dist, ...
evsize(theta,1)]), 'rndnw');
% DOA-spectrum with MUSIC and conventional beamform:
spect1 = sdoaspc('music', sig, smplPoints, 3);
spect2 = sdoaspc('cbf', sig, smplPoints);
plot both DOA spectra:
splot2(spect1,'',spect2)

6. OUR USE OF DBT

DBT is used for studies of model based methods for estimation of the number of targets and the direction to targets in radars with digital array antennas using simulated and measured [6] signals.

Multipath reflections from rough surfaces are analyzed by utilizing measurement data from the experimental antenna in an anechoic chamber. Currently, we are performing outdoor radar measurement, where DBT is used for a major part of the signal processing and presentation.

DBT will also be used for studies of space-time processing.

REFERENCES