The Design, Development and Use of a Matlab Toolbox for Radar Modeling, Simulation and Signal Processing

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Abstract: *We have developed a Matlab toolbox, called DBT, for radar modeling, simulation and signal processing. It has been successfully used in radar and array processing applications for processing of measured sensor data and for research. In this paper we want to share some experiences from the design, development and use of DBT. We also make a comparison with a new similar toolbox from Mathworks.*

1. Introduction

DBT is a software toolbox for radar modeling, simulation and signal processing [1, 2] for Matlab [16] and Octave [18], which are two environments for numerical computations using a mostly compatible programming language. The development of DBT started 1994 as a tool at FOI (Swedish Defence Research Agency) with the aim to study array processing ("DBT" meant "Digital Beamforming Toolbox") but has evolved to have a focus on radar. It therefore not only treats the space, i.e. "array", dimension but also the fast-time (range) and slow-time (pulse) dimensions, even if the space dimension still is the most developed. The objectives of DBT have been to conduct signal processing research and to process real sensor data. An earlier version of DBT and a graphical interface using Simulink have been described in [6, 8]. Compared to the version in [8], DBT now has much more functionality (three times more code and help text). A limited but free version of DBT is available for download [1] under the GNU GPL license. Mathworks, the supplier of Matlab, has recently released a toolbox similar to DBT [17]. Besides these two toolboxes, the availability of similar tools is scarce on the market. Many companies and organizations have their own tools but they do not share them.

The objectives with this paper is to share some of the experience gained from developing and using DBT. In Section 2 we describe the design and development of DBT. Then, in Section 3, the contents of the current implementation is briefly listed. Section 4 reports on the use of DBT. Section 5 contains a comparison of DBT with the Mathworks toolbox. Finally, in Section 6 some conclusions are listed.

2. Design and development

DBT is an extension to the Matlab/Octave language with new functions and data types. Fig. 1 shows the possible signal flow between processing blocks in programs using DBT. There is a data acquisition part (simulated or measured data) to the left, a linear processing part in the middle (coherent processing in space and/or time) and a detection and estimation (conventional or model based) part to the right. Most blocks need the radar models (antenna, waveform and imperfections) in the background to work.

The interfaces between the blocks in Fig. 1 are well-defined data types. The most important is RxRadarSigT, which contains received or processed signals in pulsed or FMCW radar or in a listening-only (passive) mode. RxRadarSigT contains the actual signals, i.e. the radar datacube, and metadata, i.e. information about the signals. The metadata contain the antenna & waveform definition and information about the processing history. The metadata make the handling of signals fast and easy for the user.

The most important models in DBT are the explicit steering vectors in space, fast-time, slow-time, space-slow-time and space-fast-time. A steering vector is the radar response on a signal with a certain Doppler shift incident from a certain direction and/or range. The steering vectors in space are defined by the antenna definition. The steering vectors in time are defined by the radar waveform. Using steering vectors has several advantages. In most cases the algorithm can be separated from the model, e.g. a DOA (Direction of Arrival) estimation method can be used for any antenna. Further, the algorithm can be separated from the signal dimensions, e.g. a DOA estimation method can be used for signals in space, fast-time, slow-time, space-fast-time and space-slow-time. Therefore, in principle, STAP (Space Time Adaptive Processing) [13] is not different from adaptive beamforming. With this structure, we get STAP simply by using the algorithms for the space dimension, like adaptive beamforming and DOA estimation, together with space-time steering vectors. (However, STAP usually requires other, reduced-dimension or reduced-rank, methods because of the much larger signal vector).

Another type of model in DBT are the theoretic covariance matrices of received target, jammer, clutter and noise signals. These matrices can be used for signal property studies and performance calculations and in the signal simulation and processing. The covariance matrices are generated with the steering vectors as basis.

DBT has been gradually developed to meet our needs. Much now exists in DBT but there is always something missing, which has to be added. DBT now contains about 79 000 lines of code, help text and comments. By a rough estimate, 50% are help text and comments, 45% management of signals and parameters and also error checks (the "framework"). Only 5% do the actual processing. Since the framework is the most time consuming to develop, when it exists, it is easy and quick to add new signal processing methods.

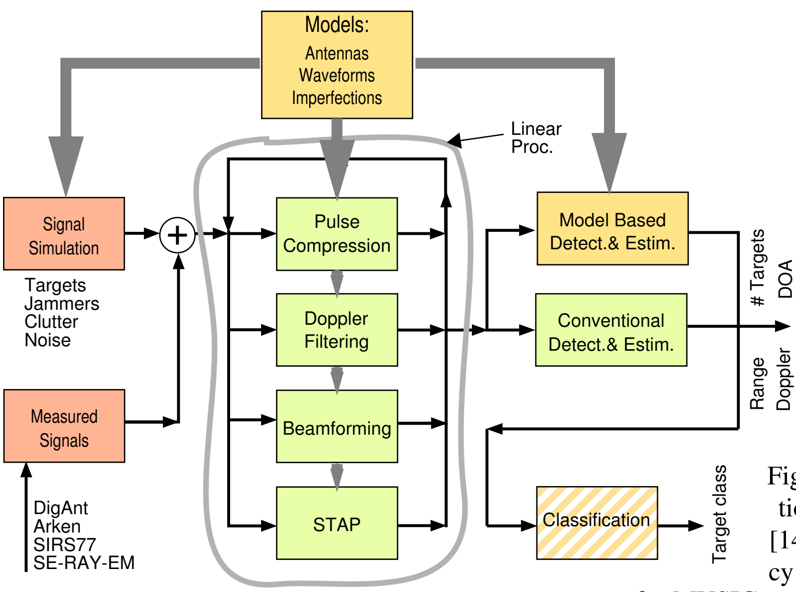

Figure. 1. Block diagram of DBT. This signal flow is built by the end user in application programs. The models consist of steering vectors and parameter structures. The "Classification" block is not in DBT.

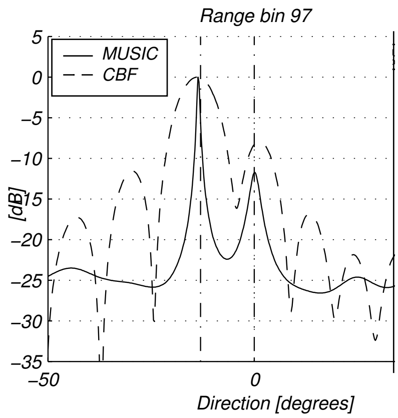

Figure. 2. Directional spectra for conventional beamforming (CBF) and MUSIC [14] at range bin 97 and doppler frequency 2.0 kHz. We know that the peak at 0° for MUSIC probably is false because of information from the conventional detection. The vertical dash dotted lines at −13° and 0° are the true DOAs. DBT was used for calibration and for management and processing of measured radar signals. Figure 17 in [9].

3. Current functionality of DBT

This section lists the most important functionality in DBT: radar modelling in Section 3.1, signal simulation and other signal acquisition in Section 3.2 and signal processing in Section 3.3.

3.1. Radar modeling

- Waveforms, which give range delays, ambiguous ranges, Doppler shifts, ambiguous Doppler and side lobes. There is pulsed radar design tool.
- Array antennas with/without subarrays. All elements can have their own position, rotation and pattern. Antenna pattern plots and antenna gain calculations.
- Modeling hardware, system and environment imperfections.
- Steering vectors in space, slow-time (pulse), fast-time (range), space-slow-time and space-fast-time.
- Theoretic monostatic and bistatic surface clutter covariance matrices.
- Computing and plotting SINR (Signal to Interference + Noise Ratio) for non-adaptive processing and optimal STAP in slow-time and fast-time.

3.2. Signal simulation and other signal acquisition

- Simulation of narrowband radar point target signals with pulse modulation and ambiguities in range and/or Doppler.
- Simulation of signals from targets with arbitrary movement, range bin migration and RCS variation with aspect angle.
- Simulation of monostatic surface clutter and jammer signals and receiver noise.
- Simulation of narrowband and wideband signals in listening-only (passive) mode, e.g. communication signals.
- Simulation of model imperfections.
- Using measured radar signals from an 3 GHz array antenna [20] with near-field and calibration compensation. Using measured radar data from a 6-18 GHz pulsed radar (called "Arken") [11], a 24 GHz pulsed radar and a 77 GHz FMCW radar.
- Using radar signals from detailed electromagnetic computations.

3.3. Signal processing

- Pulse compression, beamforming and Doppler filtering with several methods, modulations and taperings.
- Detection of radar targets with CFAR (Constant False Alarm Ratio). Estimating velocity, range and DOA of detected targets.
- Detection of radar signals in ESM (Electronic Support Measures) systems.
- Spectral and parametric DOA estimation [14].
- Estimation and modification of the spatial covariance matrix. Estimation of the number of sources.
- Spectral Doppler, range and DOA-Doppler estimation.
- Time-Doppler (micro-Doppler) analysis.
- Covariance Matrix Tapers (CMTs) to enhance the signal processing.
- Estimation of signal properties, like power, SINR (Signal to Interference+Noise Ratio) and instantaneous frequency.

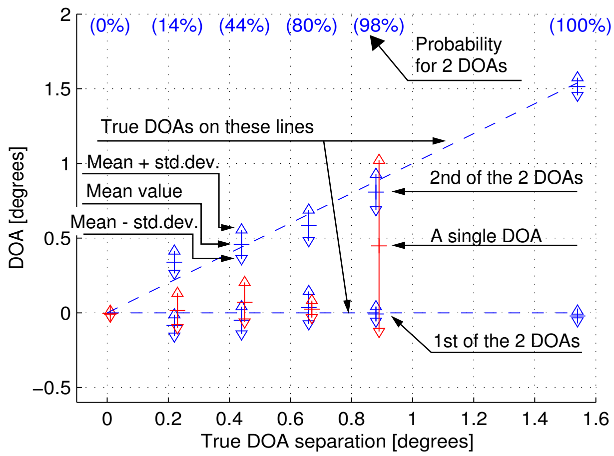

Figure. 3. Min-Norm DOA estimation [14] versus DOA separation. The mean values are shown by short horizontal lines. A vertical line is joining the two standard deviation arrows. Percent numbers at the top tell the probability of resolving the two sources. For not resolved measurements, a third vertical line with mean value and standard deviation markers for the single estimated DOA is plotted just to the right of the two vertical lines for two resolved DOAs. The true DOAs lie on the dashed lines. We see that the resolution of Min-Norm is below $1/10$ of the conventional beamwidth, which is about $10°$. DBT was used for calibration and for management and processing of measured radar signals. Figure 6 in [7].

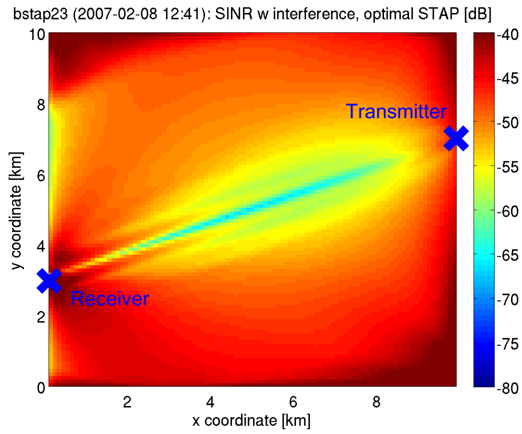

Figure. 4. SINR with optimal space-fast-time STAP. With interference (clutter, direct signal) and noise. For each target position the received signal is processed by optimal fast-time STAP to exactly that position. Stationary transmitter, receiver and target. Isotropic transmitter antenna and eight-element linear array receiver antenna. DBT was used for the modelling of the radar system and the target, clutter and direct signal via steering vectors and covariance matrices. Figure from [2].

4. The use of DBT

We have successfully used DBT in many projects, e.g. Evaluating DOA estimation methods on measured [7] (Fig. 3) and simulated data; Analyzing radar measurements in an anechoic chamber [9] (Fig. 2) and outdoors [12]; Analyzing jammer and bistatic radar measurements; Studying jamming and jammer suppression; Suppressing clutter with STAP for conformal antennas [3] (Fig. 5); Suppressing bistatic clutter with STAP [4] (Fig. 4); Analyzing micro-Doppler of moving persons [19] and vehicles (Fig. 6); Measuring signal processing properties of scattered signals [5]; Statistically analyzing radar detection by ESM and as part of a multifunction antenna simulator [10]. DBT is also used in the book [15].

Some experience with DBT is: The processing of real sensor data works. For computer simulations the steering vectors and theoretic covariance matrices are the important models, e.g. for complicated antennas and for clutter. In the clutter simulation, computing the theoretic clutter covariance matrices is slow and memory consuming. The available computer memory limits the number of pulses, range bins and antenna channels.

Some user comments on an earlier version of DBT are: “Concerning DBT. So far I have found it very easy to use. I downloaded the reference guide and am working with it. As a complete toolbox package I think you have a very good product for use in research and in the academic world.”, David Anglea, USA. “I think that you have an excellent product and I am looking forward to using it.”, Pieter Roux, South Africa. “Few years back I downloaded a very useful radar array processing toolbox (DBT) from the university web site.”, “I found the toolbox an useful means beyond the radar application (Actually I am using it mainly for sonar array simulation).”, “to me DBT is an invaluable tools”, Zou Nan, Singapore.

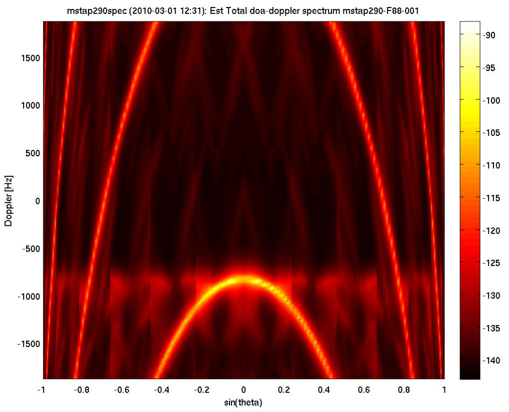

Figure. 5. Interference (clutter plus receiver noise) DOA Doppler spectrum. Forward-looking faceted half-cylinder antenna with 14 non-overlapping 8x8 facets and subarrays and moving radar. DBT was used for the modelling of the radar system and the clutter via steering vectors and covariance matrices. Figure 10 in [3].

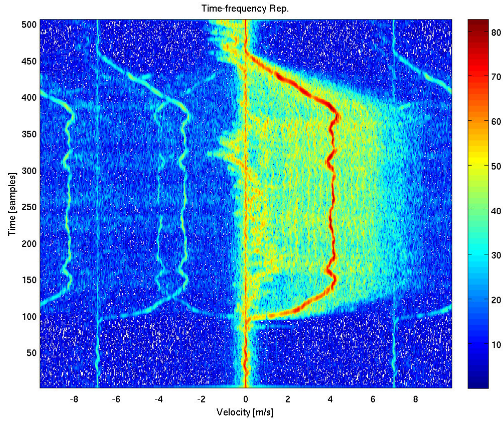

Figure. 6. Time-frequency representation on the radar pulses. Measurements on a tracked vehicle, which is stationary from the beginning, then accelerates, keeping a nearly constant speed and then brakes to still again. DBT was used for management and processing of measured radar signals. Figure from [2].

5. Comparison with Mathworks' toolbox

The new Matlab Phased Array System Toolbox (PASTB) [17] was launched 2011 by Mathworks. Comparing DBT and PASTB we notice that the functionality is similar. Also PASTB has a focus on radar even if this is not explicitly stated. DBT has also been used for non-radar applications, e.g. sonar (Section 4), ESM and general DOA estimation. There are some differences in the contents of DBT and PASTB. Some functionality and features are only present in DBT, others only in PASTB. A shortcoming of PASTB is that it cannot simulate clutter. The clutter signals used in some examples are loaded from disk. Clutter simulation is complicated and time-consuming but is required in many studies.

The architectures of DBT and PASTB are different. PASTB uses Matlab's automatic object orientation (OO) while DBT uses a kind of "manual OO". In PASTB the processing, e.g. pulse compression or DPCA clutter filter, are represented as objects but the signals are not objects. In DBT the processing are functions but the signals are objects. Thus, in Fig. 1, the connections/interfaces between the processing blocks are objects in DBT but not in PASTB while the blocks are objects in PASTB but not in DBT. The DBT way conforms better to the OO concept and we think it is easier to use.

DBT signals are packaged together with metadata, with advantages described earlier. The user of PASTB has to manage all signal metadata manually. DBT has the separation of algorithm, dimensions and model thanks to the explicit steering vectors. PASTB seems to be missing this concept. This means that the methods in PASTB are locked to some signal dimension(s).

PASTB most likely requires a recent Matlab version. It also requires two Mathworks Matlab toolboxes. DBT can be run on a recent or older Matlab version or with some changes on Octave. For some functionality, up to three Mathworks Matlab toolboxes and some free Matlab/Octave toolboxes are needed.

6. Conclusions

- The toolbox DBT for radar modeling, simulation and signal processing has successfully been used for many tasks thanks to the purposeful development of a general tool.
- The design of DBT is successful with signals being objects, which also store metadata, and with explicit steering vectors, separated from the algorithms.

- The steering vectors in the signal dimensions space, slow-time and fast-time are the central radar models. Separating the algorithms from the steering vectors, makes most algorithms usable for all signal dimensions and all models.
- DBT and the corresponding Mathworks toolbox are both usable. They have similar contents but different designs. DBT has a more general design even if it does not use Matlab's OO.

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