Estimation of Parameters Reflected Discrete Clutter Signals

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Abstract

The objective of this paper is to present an algorithm to estimate the relative ranges, angle-of-arrivals (AoAs), and Doppler frequencies of the *discrete clutter signals* depending on the measurements by a single passive receiver. A single moving emitter source is assumed in this paper. The discrete clutter signals are generated through the multipath reflections of the emitter signal. The technical challenges are identified and an algorithm to resolve them is presented. The high potential of the algorithm is demonstrated by simulation.

1 Introduction

The problem of estimating the relative ranges, angle-of-arrivals (AoAs), and Doppler frequencies of the discrete clutter signals is considered in this paper. The discrete clutters mean the strong signal reflectors such as water towers, the antennae of TV/radio broadcasting stations, large buildings, etc. We will name these parameters as the clutter parameters for simplicity. Similarly, the location and velocity of the emitter are named as the emitter parameters.

Since passive sensing is assumed in this paper, the true range of the emitter-clutter-receiver path cannot be estimated, where the relative clutter range is defined by

$$rr_k = r_k - r_e,$$

where r_e and r_k denote, respectively, the path lengths of the emitter and k -th discrete clutter.

Depending on the assumptions on the measurements and sensors, many different problems are formulated and solutions are derived [1]-[5]. Most of the previous approaches assumed *multiple* sensors placed at *known* locations. [1, 3, 4, 5].

The problem becomes significantly difficult if a *single* sensor/receiver is assumed. The sensor receives the emitter signal and the signals reflected by the discrete clutters whose number and locations are *unknown*. It is assumed in this paper that the signal-to-noise ratio (SNR) of emitter signal is significantly greater than those of the reflected discrete clutter signals.

1.1 Problem Statement

Estimation of the clutter and emitter parameters are often combined and formulated as a recursive multi-dimensional search problem [2]. Starting with some initial estimates, the emitter parameters are estimated depending on the clutter parameters, and the clutter parameters are estimated depending on the estimates of the emitter parameters. The recursion process is repeated until sufficient convergence of all of the estimated parameters is attained. Estimation accuracy depends on the initial conditions and the convergence criteria.

As stated in [2], the search problem is highly non-linear and some approximation is introduced to solve it. The approach of the present paper, however, is to decompose the problem into linear problems and to estimate the clutter parameters without iterative process of the multi-dimensional search.

A Doppler waveform is assumed as the emitter signal in this paper. The technical challenges are illustrated in Figures 1 and 2. In both figures, the large signal power indicates the emitter pulse(s). The basic technical challenged are indicated in Fig. 1. The figure shows that the clutter signals may overlap each other since the relative ranges of some discrete clutters may be approximately the same. Some clutter pulses may overlap even the emitter pulse, since these clutter signals may reach the receiver before the end of the emitter pulse. In order to estimate the clutter parameters, it is required to separate the clutter pulses not only from the emitter pulse but also from other clutter pulses.

Fig. 1: the first emitter pulse and clutter signals

Fig. 2 shows the case where the second emitter pulse is received before the end of the clutter signals that

are created by the first. It is required to eliminate the influence of the clutter signals created by the second pulse from those by the first. Overlapping clutter signals that are created by different emitter pulses makes it difficult to apply iterative algorithms to estimate the clutter ranges.

Fig. 2: The signals in blue are created by the first emitter pulse. Those in red are by the second emitter pulse.

The organization of the paper is as follows. In Section 2, an algorithm that characterizes the emitter pulse is presented. Extraction and characterization of the emitter pulses are discussed in Section 3. Section 4 is devoted to extracting clutter signals and estimation of the clutter parameters. Performance of the algorithm is examined in Section 5 where some simulation results are presented. Further work required to make the algorithm more robust and applicable under practical conditions is stated in Section 6. Conclusions are presented in Section 7.

2 Received Signal

A phased array antenna consisting of N elements is assumed for the receiver. A Doppler waveform is assumed for the emitter signal. The received signal for the n -th array element at the l -th pulse period is given by:

$$y_n(k\Delta - lT_r) = c_n p(k\Delta - lT_r) + \sum_{m=1}^M a_m p(k - \tau_{nm} - lT_r) + v_n(k\Delta), \quad l = 1, 2, \dots, L, \quad (1)$$

where the following are defined:

- L : the number of emitter pulses in a Doppler waveform
- $p(\bullet)$: emitter pulse
- c_n : complex amplitude of the emitter pulse
- a_m : complex amplitudes of the m -th clutter
- τ_{nm} : time delay of the m -th clutter pulse with respect to the emitter arrival time of the n -th array element
- T_r : pulse repetition interval (PRI)
- M : the number of clutters

- Δ : sampling interval
- $v_n(k\Delta)$: white Gaussian measurement noise sequence of the n -th antenna element

Measurement noises of different antenna elements are assumed statistically independent. In the above, only sampling interval is known, the others must be estimated.

3 Estimation of Emitter Pulse

Since the clutter signals are created by the emitter signal leaked through the emitter antenna sidelobes, it may be assumed that the power of the reflected clutter signals are significantly lower than that of the emitter pulses as indicated in Fig. 2. In order to separate the clutter signals from the emitter pulses, we capitalize on the high SNR of the emitter pulse.

3.1 Extraction of emitter pulse samples

Due to the high SNR, the signal samples that corresponds to the emitter pulses can be identified by applying appropriate threshold. In Fig. 3, an example of the selected high power samples is shown as the red dots. These high power samples are considered created by the pulses of the emitter Doppler waveform.

Fig. 3: Selected high power samples. The simple threshold was applied to get these high power samples. Sixteen pulses are assumed in this figure.

As observed in Fig.3, the high power samples are clustered. The number of pulses of the Doppler waveform can be estimated depending on the number of the clusters. Since such clusters should be separated at a constant interval for a Doppler waveform, we can determine whether or not the emitter signal is a pulse signal or not. We proceed with our discussion assuming the emitter signal is a Doppler waveform.

3.2 Determination of pulse width and pulse-repetition time

The cluster sizes can be used to determine the pulse width, and the separation between these clusters can be used to determine the pulse repetition time (PRT).

We have to note that some clutter signals may overlap the emitter pulse. Such an example is shown in Fig.4, in which one of the emitter pulses of Fig.2 is shown. The figure shows that the emitter pulse is contaminated

by the clutter signals. Such contamination may cause errors in estimating the emitter pulse. Since the SNR of the emitter signal is assumed significantly high in our case, the contamination did not cause noticeable impact on the characterization of the emitter pulse.

Fig. 4: A received emitter pulse. The signal samples of one of the emitter pulse of Fig. 2 is enlarged and shown. Non-constant amplitude indicates the presence of clutter signals.

3.3 Determination of pulse modulation

We are interested in determining whether the emitter pulse is modulated or not. As the modulation, we particularly consider the linear frequency modulation (LFM) since majority of radar pulses are either rectangular or LFM.

Let $p(t)$ denote a non-modulated pulse (i.e., simple rectangular pulse) with a width T_p by

$$p(t) = \begin{cases} c & \text{if } |t| \leq \frac{T_p}{2} \\ 0 & \text{otherwise} \end{cases}$$

The auto-correlation of $\frac{p(t)}{\|p(t)\|}$ is computed as

$$|r(t)| = \begin{cases} 1 - |t|/T_p & \text{if } |t| \leq T_p \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

Comparing the auto-correlations of the clusters of the high-power samples with that of the ideal rectangular pulse of eq.(2), we can determine whether or not the estimated pulse is a modulated pulse.

In Fig. 5, the auto-correlation of for a high-power sample cluster is shown together with that of an LFM pulse. Despite the presence of the clutter signals in the emitter pulse, it is easy to determine whether the pulse is modulated or not.

4 Extraction Clutter Signals

The first step of extracting samples of the clutter signals is to estimate the clutter relative ranges. Since the clutter pulses are generated by the emitter signal, only relative ranges can be estimated. After estimating the relative ranges of the clutters, their AoAs will be estimated by the array antenna technique.

Since a Doppler waveform is assumed in this paper, it is necessary to determine the maximum length of the interval within which all clutter signals created by

Fig. 5: Comparison of auto-correlation of an LFM pulse (blue) and high-power sample cluster (red). The auto-correlation of the cluster matches that of eq.(2).

an emitter pulse are present. We name the maximum interval as the extended pulse period (EPP). A EPP is characterized by the start time of an emitter pulse and the end time of the clutter signals created by it.

4.1 Estimation of the extended clutter periods

Among the received emitter pulses, consider the last pulse. It is easy to see that the end sample of the received signals is generated by the *last* emitter pulse. The length of the EPP can be estimated as the time difference between the start of the last pulse and the end of all clutter signals. The sample interval in red of Fig. 2 indicates the EPP.

The pulse repetition time T_r can be estimated by the length of the separations between clusters of the high power samples. Let us denote the length of the EPP by T_c . If $T_c > T_r$ holds, some clutter signals created by an emitter pulse are received after some of the subsequent pulses are received. We proceed with our discussion assuming $T_c > T_r$.

Let us discuss estimation of the relative ranges and AoAs of the discrete clutter signals in an EPP.

4.2 Estimation of relative ranges

Since the estimated emitter pulse may be assumed significantly accurate as shown in Section 3.2, we can apply conventional pulse-compression technique [6] to identify possible candidates of clutter ranges. The detections of low powers are dropped by applying an appropriate threshold.

We apply the pulse compression to all output signals of the array elements in all EPPs.

4.3 Estimation of angles of arrival

The detected relative ranges for clutter signals may not be the same for all array element outputs. Due to the presence of measurement noise, the detected ranges of a discrete clutter may vary. We cluster the detections according to the closeness of the detected ranges. For this, choose the detections of one of the array element outputs as the reference. The detected ranges of the other elements are compared to the reference range. If the deviation from the reference is less than a predetermined threshold, these detections are clustered to form a range group. Clustering is repeated for all EPPs.

A detected range of a clustered group is set to the mean value of the detected ranges in the group. An array antenna technique such as the MUSIC algorithm [7] can be applied to estimate the AoA of the group.

Using the estimated AoAs, we can compute the array steering vectors for all the range groups. We then compute the array outputs of range groups by using the corresponding steering vectors as the combining weights. The estimates of the relative ranges, AoAs and powers of the detections of the range groups are generated as a result of this process. Note that since the SNR of the emitter pulse is significantly large, an accurate range group for the emitter pulses is always created.

4.4 Estimation of Doppler Frequency

It is easy to estimate the Doppler frequency for the range group if $T_c < T_r$ holds. Each pulse period generates the same range groups. Since the groups separated by T_r are generated by the same clutter, the conventional method in [6] can be directly applied to estimate the Doppler frequency.

If $T_c > T_r$ holds, some clutter pulses that are created by an emitter pulse may reach the receiver after the subsequent emitter pulses are received by the receiver. The approach of the proposed technique is to clean the detections of the first EPP by dropping the detections corresponding to the emitter pulses in the EPPs other than the first. Let us set $M_c = \lceil \frac{T_c}{T_r} \rceil + 1$ where $\lceil x \rceil$ denotes the integer not exceeding x .

The proposed technique is as follows:

- P1 Apply the scheme of Sections 4.2 and 4.3 to the signals of each EPP. The process generates the detection groups for the EPPs.
- P2 Cluster the detection groups of the EPPs into the same groups if they are separated by T_r . Thus a cluster consists of detections of the close relative ranges and AoAs separated approximately by T_r .
- P3 Consider the first T_r period of the first EPP. The detections of this period are considered accurate since they are not influenced by the other emitter pulses. Among the detections of the first EPP, drop them if they are separated from the accurate detections by an integer multiple of N_r , where N_r denotes the number of samples in T_r . These detections correspond to the clutter pulses created by the pulses other than the first.
- P4 Note that the detections of the second T_r are created by the detections of the first and second pulses only. Since the processing of (P3) eliminates the detections corresponding to the second emitter pulse, the remaining detections of the second T_r period are regarded as the accurate detections of the clutter signals created by the first emitter pulse.

- Consider the detections in the k -th T_r period, where $k \geq 3$. Set $k = 3$.

P5 Drop all cluster groups if they are separated from the $(k - 1)$ -th accurate detections by an integer multiple of N_r . This process eliminates duplicate detections by all k -th pulses, resulting in the k -th accurate detections.

P6 Set $k = k + 1$ and repeat the cleaning process of (P5) to clean the k -th T_r period.

P7 Stop if $k = M_c + 1$.

At the end of the process, all duplicate detections are eliminated. Among the detections in all EPPs, keep the resulting range groups that match with the detected ranges of the first EPP created through (P1)-(P6). The conventional method [6] can be applied to the resultant range groups to estimate their Doppler frequencies.

5 Numerical Example

The emitter and clutter signals are generated according to the following assumptions:

- an array antenna of a cross-structure is considered. There is one row consisting of eleven elements and one column of ten elements
- emitter Doppler waveform consists of sixteen pulses
- the emitter pulse repetition frequency is set to 3 (KHz)
- the received emitter pulse SNR is 70(dB)
- there are thirty discrete clutters. Their 3D coordinates are randomly generated. Their SNRs are set to 15(dB) for simplicity
- the Doppler frequency of the emitter is set to -255.7274 (Hz)
- the band width of the emitter signal is set to 2.0 (MHz)
- the sampling rate is set to 20(MHz)
- rectangular pulse is assumed for the emitter pulse

The simulated geometrical relations among the emitter, receiver, and discrete clutters are shown in Fig. 6. These clutter locations are generated randomly except that they are placed between the emitter and receiver. The direct signal path is indicated by the red arrow in the figure.

The received signal of one of the antenna elements for the emitter-clutter-receiver configuration of Fig. 6 is shown in Fig. 3. It was found that $M_c = 5$ in this case.

Fig. 6: Simulated geometry between the emitter and clutters. Red dot indicates the emitter location and the blue square the receiver location, and the blue circles the clutter locations. Thirty-one discrete clutters are present in this example. The red arrow indicates the direct path from the emitter to receiver.

The simulation results are shown in Figures 7-11. In Fig. 7, the estimated and true Doppler frequencies are compared. A red cross without blue circle in its vicinity indicates that the algorithm did not *accurately* detect the corresponding clutter pulses and thus dropped them. The figure indicates that there are six clutters that were not detected by the algorithm in this simulation.

Fig.8 shows the estimation error of the detected clutter ranges. Estimation error less 25 (m) can be considered good.

Fig. 7: Estimated Doppler frequency. The red crosses without blue circles indicate that the algorithm failed to detect the clutter pulse.

Fig. 8: Estimated range error. Errors of the detected clutters are shown.

Figures 9 and 10 show the AoA estimation error for

the detected clutter pulses. Since maximum elevation angle is 7.5×10^{-3} (rad), the maximum estimation error less than 9.0×10^{-4} (rad) can be regarded good. For estimation of the azimuthal angles, the maximum estimation error less than 2.0×10^{-3} (rad) can be regarded extremely good considering the maximum azimuthal angle of the clutters is 1.529 (rad).

Fig. 9: Estimated azimuth error. Errors of the detected clutters are shown.

Fig. 10: Estimated elevation error. Errors of the detected clutters are shown.

Fig. 11: Doppler estimation error. Doppler estimation errors of the detected clutter are shown.

Fig. 11 shows the estimation errors of the Doppler frequencies for the detected clutters. As observed, the estimates with small errors are concentrated in short ranges from the start of the first T_r pulse period, since the received signals in this interval are not contaminated by other pulses. Considering the maximum of the Doppler shifts of all clutters is 835 (Hz), the maximum error less than 16 (Hz) can be regarded as good.

6 Further Work

Similar results (not shown in this paper) were also obtained when a LFM waveform is assumed for the emit-

ter pulse. Since the parameters that characterize the rectangular or LFM pulses are well-known, they can easily be estimated.

In practice, the shape of the emitter pulse may not be known at all although majority of radar pulses are either rectangular or LFM. It is necessary to make the algorithm sufficiently robust against even unknown emitter pulse types. With a slight modifications of the algorithm, it was possible to estimate the clutter parameters for barrage interference signals (not shown in this paper.) Work is currently being continued to make the algorithm robust against the completely unknown emitter Doppler waveforms.

7 Conclusions

The technical challenges of the clutter parameter estimation are discussed and an algorithm to estimate them is presented. The approach of the present paper is to decompose the highly non-linear problem into small problems to which linear algorithms are applied. As a result, the iterative computations that is usually applied to solve non-linear problems are eliminated.

Accurate simulation results indicate the high potential of the proposed algorithm. It was shown possible to identify bad estimates by clustering detections and applying appropriate thresholds to the estimated relative ranges, AoAs, and Doppler frequencies.

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