ROBUST MOTION PARAMETER ESTIMATION IN MULTISTATIC PASSIVE RADAR

Saurav Subedi, Yimin D. Zhang, Moeness G. Amin

Center for Advanced Communications
Villanova University
Villanova, PA 19085, USA

Braham Himed

Air Force Research Laboratory
ARFL/RYMD
Dayton, OH 45433, USA

ABSTRACT

In this paper, we develop a new algorithm for motion parameter estimation of moving targets in a multistatic passive radar. Existing methods for motion parameter estimation rely on the estimated Doppler signatures of the observed signals corresponding to each transmitter. These techniques may fail for weak signals where the individual Doppler signature cannot be properly estimated. The focus of this paper is on motion parameter estimation from weak signals observed using multiple illuminators. Utilizing the sparsity of the motion parameters, the proposed technique obtains robust motion parameter estimates through the fusion of the data corresponding to all available illuminators, achieving signal enhancement and multistatic diversity. To reduce the computational cost, the acceleration and velocity parameters are decoupled and sequentially estimated.

Index Terms— multistatic passive radar, target tracking, motion parameter estimation, compressive sensing

1. INTRODUCTION

Multistatic passive radar (MPR) systems use existing broadcast or communication infrastructures, such as FM radio, digital television (e.g., DVB-T), digital radio (e.g., DAB), and cellular telephony, as the illuminators of opportunity [1, 2]. These sources form a non-cooperative group of transmitters that illuminate targets under contention. Detection and tracking of moving targets, based on the echo signals received at single or multiple receiver locations, has emerged as an area of interest (e.g., [3, 4]). The increasing interests towards passive radars can be attributed to the fact that they offer distinct advantages over conventional active radar systems, primarily in terms of their low cost and covertness. Passive radars also prevent exacerbating the problem of spectral congestion because they do not emit any radio signals.

Motion parameter estimation of ground targets has been extensively studied, particularly for conventional radar platforms. Extensive literature is available in the field of signal processing for motion parameter estimation, including time-frequency analysis, motion compensation, and range migration compensation (e.g., [5, 6]). On the other hand, MPR is less studied and there are several open challenges, specifically for motion parameter estimation. Unlike conventional radar systems which operate in a monostatic mode with a wide bandwidth and a high power, MPR systems are characterized by an extremely narrow signal bandwidth, low signal power, bistatic operation, and the availability of multiple illuminators. In the context of target detection and tracking, including motion parameter estimation, MPR systems offer a unique platform to effectively fuse the observed data corresponding to different illuminators so that robustness can be achieved in weak signal environments [7].

Because of the narrow signal bandwidth, MPR systems generally have a poor bistatic range resolution. As such, a longer coherent processing time (CPI) should be exploited in MPR as compared to the conventional radar systems. Moderate CPI can be achieved even when no compensation to range migration is applied [8]. This allows motion parameter estimation for both target velocity and acceleration.

In [8], motion parameter estimation is considered for ground moving targets, where the receiver is a moving aerial vehicle. Parameter estimation is achieved by exploiting the Doppler signatures, which are characterized as chirp waveforms, estimated in each bistatic link. The target motion parameters are estimated through a mapping of the chirp parameters, which are estimated using time-frequency analyses, corresponding to multiple illuminators. This method is effective when the signal power is sufficiently high to allow individual chirp parameter estimation of each bistatic path. However, when the signals are very noisy, the chirp parameters cannot be reliably estimated, rendering this approach ineffective.

In this paper, we focus on weak signal conditions. The received signals corresponding to all available illuminators are used to determine the motion parameters. Because of the sparsity of the motion parameters, this problem can be solved using sparsity-based signal reconstructions (i.e., maximum likelihood search or the l_1-norm signal reconstructions). However, the four dimensions of the velocity and acceleration

The work of S. Subedi, Y. D. Zhang, and M. G. Amin is supported in part by a subcontract with Dynetics, Inc. for research sponsored by the Air Force Research Laboratory (AFRL) under Contract FA8650-08-D-1303.

may cast this approach as prohibitively complex. As such, we propose an alternative technique that estimates the acceleration and velocity sequentially. First, we estimate target acceleration by fusing all the signal observations mapped into the ambiguity function of the respective Doppler signatures and then detect the combined peaks. The estimate of the acceleration is then utilized to determine the target velocity. With the reduced dimensions from four (two acceleration components and two velocity components) to two (two velocity components only), the parameter estimation problem becomes much more feasible to solve. As an example, we use a sparse signal recovery technique by constructing a dictionary matrix whose columns represent received signal vectors for a range of target velocities with the estimated target acceleration.

The following notations are used in this paper. A lower (upper) case bold letter denotes a vector (matrix). $(.)^*$ and $(.)^T$ respectively denote complex conjugation and transpose operations. $\|\cdot\|_1$ and $\|\cdot\|_2$ respectively denote the l_1 and l_2 norm of a vector.

2. SIGNAL MODEL

We consider a standard MPR system with N broadcast stations located at $\mathbf{t}^{(i)}$, $i=1,...,N$. The locations of these stations are stationary and precisely known. It is assumed that the broadcast stations use orthogonal waveforms, e.g., by the virtue of having nonoverlapping frequency spectra, which are respectively centered at $f^{(i)}$, $i=1,...,N$. An airborne receiver is assumed to be moving at a constant velocity $\mathbf{v}_r$ along the x-axis. As such, the trajectory of the receiver at time t is expressed as

$$\mathbf{r}(t) = \mathbf{r}_0 + \mathbf{v}_r t, \tag{1}$$

where $\mathbf{r}_0$ is the initial position of the receiver. On the other hand, the trajectory of the moving target is defined as

$$\mathbf{p}(t) = \mathbf{p}_0 + \mathbf{v}t + \frac{1}{2}\mathbf{a}t^2, \tag{2}$$

where $\mathbf{p}_0$, $\mathbf{v}$, and $\mathbf{a}$ are, respectively, the initial target position, initial velocity, and acceleration vectors. All these parameters are defined in three-dimensional (3-D) cartesian coordinate system. Because only ground targets are considered, the z-axis components of $\mathbf{p}_0$, $\mathbf{v}$, and $\mathbf{a}$ are assumed to be 0.

The direct range between the ith illuminator and the receiver, corresponding to the reference channel, is defined as

$$r^{(i)}(t) = \|\mathbf{r}(t) - \mathbf{t}^{(i)}\|, \tag{3}$$

whereas the bistatic range between the ith transmitter, the target, and the receiver is expressed as

$$\rho^{(i)}(t) = \|\mathbf{p}(t) - \mathbf{t}^{(i)}\| + \|\mathbf{p}(t) - \mathbf{r}(t)\|. \tag{4}$$

Therefore, the direct path signal received from the ith transmitter is defined as

$$s_{\mathrm{r}}^{(i)}(t) = u^{(i)}[t - r^{(i)}(t)/c] \exp\left[-j2\pi f^{(i)} r^{(i)}(t)/c\right] + n_{\mathrm{r}}^{(i)}(t), \tag{5}$$

where the subscript "r" represents the reference channel, $u^{(i)}(t)$ is the baseband representation of the signal transmitted from the ith illuminator, c is the velocity of wave propagation. Since passive radars use broadcast signals, it can be assumed that the transmitted signal is perfectly reconstructed at the receiver after demodulation and forward error correction [9]. The reference signal can, therefore, be expressed as

$$s_{\mathrm{r}}^{(i)}(t) = u^{(i)}(t - r^{(i)}(t)/c) \exp\left(-j2\pi f^{(i)} r^{(i)}(t)/c\right). \tag{6}$$

The surveillance signal reflected from the target, on the other hand, is given for the ith illuminator by,

$$\begin{aligned} s_{\mathrm{s}}^{(i)}(t) = {} & \sigma^{(i)} u^{(i)}(t - \rho^{(i)}(t)/c) \exp\left(-j2\pi f^{(i)} \rho^{(i)}(t)/c\right) \\ & + n_{\mathrm{s}}^{(i)}(t), \end{aligned} \tag{7}$$

where the subscript "s" denotes the surveillance channel, $\sigma^{(i)}$ is the target reflection coefficient, and $n_{\mathrm{s}}(t)$ is the additive noise.

Because the passive radar receiver does not know the exact timing of the signal transmission, it finds the range difference between the bistatic transmitter-target-receiver range and the direct transmitter-receiver range by correlating the surveillance signal and the reference signal. Denote Δt as the azimuthal sampling interval time used in the matched filtering, and $t_m = m\Delta t$ be the azimuthal sampling instants, $m = 1,...,M$. Then, the range difference at the M azimuthal sampling instants can be expressed as

$$\begin{aligned} R^{(i)}(t_m) &= \rho^{(i)}(t_m) - r^{(i)}(t_m) \\ &= \|\mathbf{p}_0 + \mathbf{v}t_m + \mathbf{a}t_m^2/2 - \mathbf{t}^{(i)}\| \\ &\quad + \|\mathbf{p}_0 + \mathbf{v}t_m + \mathbf{a}t_m^2/2 - \mathbf{r}_0 - \mathbf{v}_r t_m\| \\ &\quad - \|\mathbf{r}_0 + \mathbf{v}_r t_m - \mathbf{t}^{(i)}\|. \end{aligned} \tag{8}$$

In the above expression, the motion of the receiver platform is the dominant source of range migration. When a specific ground region is of interest, we can compensate for the range migration due to movement of the radar platform by focusing on that specific region utilizing the known motion parameters of the receiver [8]. For this purpose, a ground reference position, referred to as the scene origin, is chosen to be within a close vicinity of the actual target. Considering a scene origin at $\mathbf{q}$, the bistatic range can be calculated as

$$\zeta^{(i)}(t_m) = \|\mathbf{q} - \mathbf{t}^{(i)}\| + \|\mathbf{q} - \mathbf{r}(t_m)\|. \tag{9}$$

The corresponding delay, $\zeta^{(i)}(t_m)$, is used in the matched filtering to replace $r^{(i)}(t_m)$ in (8), as such the range difference can be expressed as

$$\begin{aligned} \tilde{R}^{(i)}(t_m) &\approx \rho^{(i)}(t_m) - \zeta^{(i)}(t_m) \\ &= \|\mathbf{p}_0 + \mathbf{v}t_m + \mathbf{a}t_m^2/2 - \mathbf{t}^{(i)}\| \\ &\quad + \|\mathbf{p}_0 + \mathbf{v}t_m + \mathbf{a}t_m^2/2 - \mathbf{r}_0 - \mathbf{v}_r t_m\| \\ &\quad - \|\mathbf{q} - \mathbf{t}^{(i)}\| - \|\mathbf{q} - \mathbf{r}_0 - \mathbf{v}_r t_m\|. \end{aligned} \tag{10}$$

3. MOTION PARAMETER ESTIMATION

The output of the receiver matched filter at azimuthal time t_m corresponding to the ith illuminator, after range compensation due to the motion of the receiver platform at the scene origin, is expressed as

$$s^{(i)}(t_m) = \xi^{(i)} \exp\left(-j2\pi f^{(i)} \tilde{R}^{(i)}(t_m)/c\right) + n^{(i)}(t_m), \quad (11)$$

where $\xi^{(i)}$ is the magnitude of the matched filter output, $n^{(i)}(t_m)$ is the noise output. The phase term is determined by the range difference, depicted in (10). For a moderate CPI time considered in the underlying problem, the Doppler signature can be considered as a chirp, i.e., the phase term of $s^{(i)}(t_m)$, denoted as $\phi^{(i)}(t_m)$, follows the following quadratic relationship,

$$\phi^{(i)}(t_m) = \phi_0^{(i)} + 2\pi f_0^{(i)} t_m + \pi \beta^{(i)} t_m^2, \quad (12)$$

where $\phi_0^{(i)}$ is the initial phase, $f_0^{(i)}$ is the initial Doppler frequency, and $\beta^{(i)}$ is the chirp rate.

3.1. Existing Technique

In [8], a motion parameter estimation technique is developed based on the time-frequency analysis for the Doppler signatures of the received signals. From the phase information revealed from (10) – (12), we can establish the following relationship between the motion parameters (acceleration vector $\mathbf{a}$ and initial velocity vector $\mathbf{v}_0$) and the chirp parameters (chirp rate $\beta^{(i)}$ and initial frequency $f_0^{(i)}$, $i = 1, ..., N$) of the Doppler signatures corresponding to all N illuminators:

$$\begin{bmatrix} f_0^{(i)} \\ \beta^{(i)} \end{bmatrix} = \mathbf{A}^{(i)} \begin{bmatrix} \mathbf{v} \\ \mathbf{a} \end{bmatrix}, \quad (13)$$

where

$$\mathbf{A}^{(i)} = -\frac{1}{\lambda^{(i)}} \begin{bmatrix} \frac{(\mathbf{q}-\mathbf{t}^{(i)})^T}{\|\mathbf{q}-\mathbf{t}^{(i)}\|} + \frac{(\mathbf{q}-\mathbf{r}_0)^T}{\|\mathbf{q}-\mathbf{r}_0\|} & \mathbf{0} \\ \frac{2\mathbf{v}_r^T}{\|\mathbf{q}-\mathbf{r}_0\|} & \frac{(\mathbf{q}-\mathbf{t}^{(i)})^T}{\|\mathbf{q}-\mathbf{t}^{(i)}\|} + \frac{(\mathbf{q}-\mathbf{r}_0)^T}{\|\mathbf{q}-\mathbf{r}_0\|} \end{bmatrix}, \quad (14)$$

and $\lambda^{(i)}$ is the wavelength of the signal transmitted from ith illuminator.

It is clear in (13) that there are four unknown motion parameters of the target, i.e., both velocity and acceleration in the x and y directions. As the time-frequency analysis of azimuthal samples of the received signal corresponding to each transmitter yields two quantities, the chirp rate and the initial Doppler frequency, we can estimate the four motion parameters using two illuminators. The use of more transmitters will yield an overdetermined problem for improved accuracy of estimation.

3.2. Proposed Technique

In the following, we focus on the low signal-to-noise ratio (SNR) situation where reliable chirp parameter estimation for each bistatic link is not possible. As such, the existing technique summarized in the previous subsection becomes inapplicable. An MPR system, utilizing signals transmitted from multiple illuminators, may nevertheless accumulate sufficient signal power to warrant robust motion parameter estimations. Towards this end, parameter estimation should proceed only *after* all signals are properly fused. Because each illuminator yields a different Doppler signature, however, parameter fusion in the time-frequency domain is rather difficult.

We consider the acceleration and the velocity as the common sparse support shared by the Doppler signatures corresponding to different illuminators. This concept has been applied in distributed compressive sensing (e.g., [10, 11]). In the underlying problem, however, we need four dimensions of unknown variables (two dimensions of the acceleration and two dimensions of the velocity) to perform a commonly used l_1-norm based sparse signal reconstruction. While such approach can handle the motion parameter estimation for multiple targets, the high-dimensional operation renders such processing very complicated, if not impractical. Therefore, we deploy a two-step estimation process, one for the acceleration and the other for the velocity, to estimate the motion parameters of a single target. These steps are detailed in the remainder of this subsection.

A. Estimation of Target Acceleration

To decouple the target acceleration vector $\mathbf{a}$ from the velocity vector $\mathbf{v}_0$, and the Doppler chirp rate $\beta^{(i)}$ from the initial frequency $f_0^{(i)}$, we notice the following two properties: (1) The effect of the off-diagonal term in matrix $\mathbf{A}^{(i)}$, i.e., the term $\frac{2\mathbf{v}_r^T}{\|\mathbf{q}-\mathbf{r}_0\|}$, is insignificant. By ignoring this term, matrix $\mathbf{A}^{(i)}$ becomes block diagonal. That is, the Doppler chirp rate $\beta^{(i)}$ only depends on the target acceleration vector $\mathbf{a}$, and the initial frequency $f_0^{(i)}$ only depends on the velocity vector $\mathbf{v}_0$. (2) When a chirp signal is considered in the ambiguity domain, its signature is not affected by its initial frequency. With these two properties, the acceleration vector $\mathbf{a}$ is fully decoupled from $\mathbf{v}_0$ as well as $f_0^{(i)}$. In this case, the chirp rate is solely a function of target acceleration and is expressed as

$$\beta^{(i)} = -\frac{1}{\lambda^{(i)}} \left(\frac{\mathbf{q}-\mathbf{t}^{(i)}}{\|\mathbf{q}-\mathbf{t}^{(i)}\|} + \frac{\mathbf{q}-\mathbf{r}_0}{\|\mathbf{q}-\mathbf{r}_0\|} \right)^T \mathbf{a}. \quad (15)$$

The ambiguity function of signal $s^{(i)}(t_m)$ is defined in the discrete-time representation as [12]

$$\chi^{(i)}(\theta,\tau) = \sum_{m=1}^{M} s^{(i)}(t_m-\tau) \left[s^{(i)}(t_m+\tau) \right]^* \exp(-j2\pi\theta t_m). \quad (16)$$

For a waveform that is characterized by its chirp Doppler signature, the ambiguity function is a straight line passing through the origin, irrespective of the initial Doppler frequency, where the slope of the straight line is determined by the chirp rate $\beta^{(i)}$.

By varying a_x and a_y within the maximum possible range, we can obtain the chirp rate $\beta^{(i)}_{a_x,a_y}$ corresponding to each illuminator according to (15). The contribution of each illuminator can be coherently combined along their respective ambiguity function signature determined. As such, the estimated target acceleration, $[\hat{a}_x, \hat{a}_y]^T$, is determined as

$$[\hat{a}_x, \hat{a}_y] = \arg\max_{a_x,a_y} \sum_{\tau} \left| \chi^{(i)}(\theta^{(i)}(\tau), \tau)[\chi^{(i)}_{a_x,a_y}(\theta^{(i)}(\tau), \tau)]^* \right|, \tag{17}$$

where

$$\theta^{(i)}(\tau) = \beta^{(i)}\tau = -\frac{\tau}{\lambda^{(i)}} \left(\frac{\mathbf{q} - \mathbf{t}^{(i)}}{\|\mathbf{q} - \mathbf{t}^{(i)}\|} + \frac{\mathbf{q} - \mathbf{r}_0}{\|\mathbf{q} - \mathbf{r}_0\|} \right)^T \begin{bmatrix} a_x \\ a_y \\ 0 \end{bmatrix}, \tag{18}$$

and $\chi^{(i)}_{a_x,a_y}(\theta, \tau)$ is the ambiguity function of hypothesis waveform $\tilde{s}(t) = \exp(j\pi\beta_{a_x,a_y}t^2)$.

B. Estimation of Target Velocity

Once the acceleration vector is estimated, the problem becomes the estimation of the velocity vector, which contains v_x and v_y. One approach to solve the velocity vector is to formulate a standard sparse signal reconstruction problem. Define $\mathbf{y}$ as the NM-element complex vector which stacks the matched filter output corresponding to the N illuminators. The output corresponding to each illuminator contains M azimuthal samples. An $N_xN_y \times 1$ vector $\mathbf{u}$ with unknown and sparse entries, which vectorizes the discretized 2-D velocity indexes, is to be estimated, where $N_x \times N_y$ denotes the search grid of the 2-D velocity. Let the kth entry of $\mathbf{u}$ be associated with $v_x^{[k]}$ and $v_y^{[k]}$, and the initial Doppler frequency corresponding to the ith illuminator be $f_0^{(i),[k]}$. Then, the kth column of the $NM \times N_xN_y$ dictionary matrix $\mathbf{G}$ is expressed as

$$\begin{aligned}\mathbf{g}_k = \; & [w^{(1)} \exp(-j\tilde{\phi}^{(1),[k]}(t_1)), ..., w^{(1)} \exp(-j\tilde{\phi}^{(1),[k]}(t_M)), \\ & w^{(2)} \exp(-j\tilde{\phi}^{(2),[k]}(t_1)), ..., w^{(2)} \exp(-j\tilde{\phi}^{(2),[k]}(t_M)), \\ & \vdots \\ & w^{(N)} \exp(-j\tilde{\phi}^{(N),[k]}(t_1)), ..., w^{(N)} \exp(-j\tilde{\phi}^{(N),[k]}(t_M))]^T,\end{aligned} \tag{19}$$

where $w^{(i)}$ is a weight coefficient,

$$\tilde{\phi}^{(i),[k]}(t_m) = \phi_0^{(i)} + 2\pi f_0^{(i),[k]} t_m + \pi\hat{\beta}^{(i)} t_m^2, \tag{20}$$

and

$$\hat{\beta}^{(i)} = -\frac{1}{\lambda^{(i)}} \left(\frac{\mathbf{q} - \mathbf{t}^{(i)}}{\|\mathbf{q} - \mathbf{t}^{(i)}\|} + \frac{\mathbf{q} - \mathbf{r}_0}{\|\mathbf{q} - \mathbf{r}_0\|} \right)^T \begin{bmatrix} \hat{a}_x \\ \hat{a}_y \\ 0 \end{bmatrix} \tag{21}$$

is the chirp rate estimated corresponding the estimated acceleration parameters $\hat{a}_x$ and $\hat{a}_y$.

The problem of velocity estimation can, thus, be formulated as the following l_1-norm problem,

$$\min ||\mathbf{u}||_1 \quad \text{subject to} \quad \mathbf{y} = \mathbf{G}\mathbf{u}, \tag{22}$$

which can be solved by a number of methods being available for sparse signal reconstruction. We use the Compressive Sampling Matching Pursuit (CoSaMP) [13] algorithm, and the number of iterations is chosen to be one. The only non-zero element in the solution corresponds to the index of the estimated target velocity.

4. SIMULATION RESULTS

We consider a geolocation scenario, as illustrated in Fig. 1, where five DAB transmitters are respectively located at $[-12, 10, 0.1]^T$ km, $[15, -15, 0.1]^T$ km, $[12, 20, 0.1]^T$ km, $[-15, -10, 0.1]^T$ km, and $[20, 5, 0.1]^T$ km. The respective carrier frequencies of these five illuminators are 220, 222, 224, 226, and 228 MHz. The initial receiver position is $[0, 0, 5]^T$ km, and it moves with a constant velocity of $[150, 0, 0]^T$ m/s. The initial position of the target is at $[0, 14, 0]^T$ km and it moves with an initial velocity of $[10, 10, 0]^T$ m/s and an acceleration of $[3, 4, 0]^T$ m/s^2. The scene origin is chosen to coincide with the initial target position, i.e., $[0, 14, 0]^T$ km.

The receiver data is sampled at 2.048 MHz, and the matched filter output yields a 200 Hz azimuthal sampling frequency. The overall CPI time is assumed to be 1 second, which generates 200 azimuthal samples per illuminator. The input SNR is assumed to be -52 dB for all the illuminators. Note that situations with a lower SNR can be handled when more illuminators are available.

Fig. 2 depicts the spectrogram of the azimuthal samples corresponding to the first illuminator, where a Hamming window of length 51 is used. It is clear from this figure that, at the low SNR level of -52 dB, the Doppler signature cannot be clearly identified for reliable chirp parameter estimation. Reliable chirp parameter estimation cannot be achieved with other approaches, such as the Radon-Wigner transform or the Fractional Fourier transform.

In Fig. 3, we demonstrate that accurate motion parameter estimates are obtained using the proposed method. The white dot indicates the estimated result in each picture. The estimated acceleration and velocity vectors in this realization are respectively $[3.6, 4.0, 0]^T$ m/s^2 and $[9.6, 10.2, 0]^T$ m/s. Through 50 independent trials, we obtain the root-mean-square error (RMSE) of $[0.71, 0.26, 0]^T$ m/s^2 for the acceleration and $[0.35, 0.26, 0]^T$ m/s for the velocity.

5. CONCLUSIONS

In this paper, we have developed a method for the estimation of motion parameters of moving target in a multistatic passive radar platform. We consider weak signal scenarios where a number of illuminators are available but the signal-to-noise ratio (SNR) of each individual bistatic link is low. As such, existing techniques that are based on the Doppler signature parameter estimation are not applicable. In the proposed method, robust motion parameter estimation is achieved by fusing the observations corresponding to all available illuminators. A two step algorithm is proposed to sequentially estimate the target acceleration and the velocity with a very low computational cost. Simulation results were presented to demonstrate the effectiveness and robustness of the proposed method in low SNR situations.

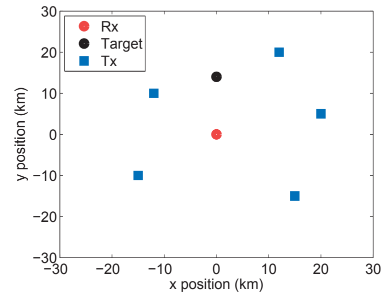


Fig. 1. MPR geometry.

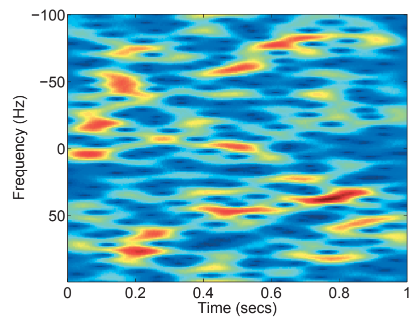
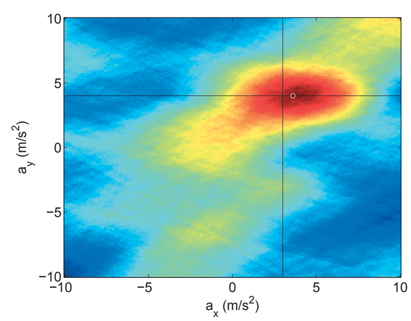
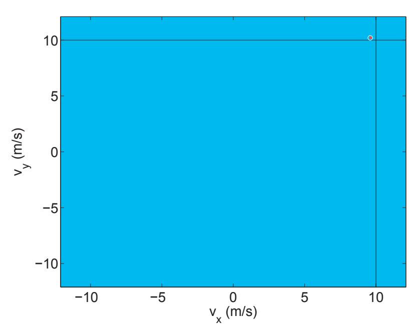


Fig. 2. Spectrogram of the azimuthal data samples.



(a) acceleration



(b) velocity

Fig. 3. Motion parameter estimation result.

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