Comparison of clutter rejection techniques for measurement of small displacements of body surface using radar

S. Okumura✉, T. Sakamoto, T. Sato, M. Yoshioka, K. Inoue, T. Fukuda and H. Sakai

To measure vital signs using Doppler radar, a common approach involves the use of time-varying echo phase. To acquire these measurements, clutter rejection is necessary because clutter power is often larger than echo power. To reject static clutter, several techniques have been proposed that assume relatively large phase rotation angles because many studies assume the measurement of the upper torso, where displacement is mainly caused by respiration. However, signals from other parts of the human body are known to have smaller displacements that exhibit small phase rotation angles, which make clutter rejection more difficult. Three clutter rejection techniques for measuring small displacements are compared and their performances are investigated. Using numerical analysis, one method is demonstrated to be the most effective, even for small displacements in noisy data. The best method successfully estimates the centre with an error of −13.4 and −24.0 dB, with a signal-to-noise ratio of 10 and 40 dB and the range of phase rotation angles of 90° and 15°.

Introduction: Contactless vital monitoring using Doppler radar is a promising technique for health care applications [1–6]. The radar measures vital signs by quantifying the displacement of the body's surface, which is caused by the heartbeat and respiration. The surface displacement causes phase rotations in the radar signal. However, in realistic scenarios, radar signals contain static clutters that interfere with the time-dependent vital sign components. Thus, clutter rejection is essential for accurate vital sign monitoring using Doppler radar [1–6]. Recent studies [7, 8] have reported that ultra-wideband radar mitigates the influence of static clutters by using time gating. Despite this, when the target and clutter are in the same range bin, the clutter must be rejected.

The echo phase is sensitive to small displacements of a human body, while the echo power is almost unchanged. As a result, echoes containing vital signs tend to exhibit circular motion in the *I–Q* plane. Static clutter corresponds to a direct current component that appears as the centre of a circle. The radar signal is the sum of these echoes and static clutters. Therefore, estimating the centre of the circle in the *I–Q* plane facilitates static clutter rejection. Several techniques have been proposed [1, 5, 6, 9] to address this estimation problem.

A comprehensive review has been published [1] that compares representative clutter rejection methods proposed by Zakrzewski *et al.* [1], Park *et al.* [5] and Yuen and Feng [9]. The authors conclude that the Park method and Zakrzewski method are effective when the target participant is breathing calmly, and the Zakrzewski method performs best when the participant is breathing deeply. The Park method estimates the circle using heuristic estimation with axis rotation using principal component analysis (PCA). The Zakrzewski method fits the circle in the *I–Q* plane using the least mean square (LMS) method combined with the Levenberg–Marquardt method.

Many techniques assume relatively large phase rotation angles, such that 90° and 47° [1, 5], because they assume the measurement of an upper torso where displacement is mainly due to respiration. However, signals from other parts of the human body, such as the shoulder or sole, have displacements that produce smaller phase rotation angles. The range of phase rotation depends on the frequency, where a higher frequency makes it easier to estimate the circle's centre.

A recent publication shows that the heartbeat can be accurately estimated from the soles [8]. The displacement of the sole's surface is much smaller than that of the chest wall, leading to a phase rotation <45° for the frequency band of 60 GHz. Furthermore, the phase rotation of signals from the non-breathing chest wall and shoulder are also small. Thus, there is a demand for a technique to reject static clutters that is effective for small displacements. In this Letter, we compare and evaluate three methods – proposed by Park *et al.* [5], Zakrzewski *et al.* [1], and Hu *et al.* [6] – and conclude that the Hu method has the most effective clutter rejection capability for signals with small phase rotations.

System model: A radar signal $s(t)$ containing a static clutter and an echo from a moving target with a displacement of $x(t)$ is modelled as

$$s(t) = A\exp(\mathrm{j}\phi(t)) + A_\mathrm{c}\exp(\mathrm{j}\phi_\mathrm{c}) + N \tag{1}$$

$$\phi(t) = \frac{4\pi x(t)}{\lambda} \tag{2}$$

where t is the slow time, A is the amplitude of the desired signal, $\phi(t)$ is the phase rotation angle, λ is the wavelength at the centre frequency, A_c is the clutter amplitude, ϕ_c is the phase of clutter, and N is Gaussian complex noise. In this Letter, we assume the *I–Q* channels are perfectly balanced.

Heuristic centre estimation using PCA (Park method): Park *et al.* [5] propose a method to estimate static clutters using a heuristic estimator after PCA-based axis rotation. The axis is rotated using the eigenvector of the data's covariance matrix that corresponds to the largest eigenvalue. Their method is given by

$$k(m, n) = \frac{s'^2_{Im} + s'^2_{Qm} - s'^2_{In} - s'^2_{Qn}}{2(s'_{Im} - s'_{In})} \tag{3}$$

$$k_P = \underset{m \neq n}{\mathrm{median}}\,\{k(m, n)\} \tag{4}$$

where m and n are data indices, s'_I and s'_Q are the I and Q signal components after the axis rotation, and k_P is the centre of the circle on the rotated axis. The centre of circle is calculated by multiplying k_P with the inverse of rotation matrix.

Circle fitting using Levenberg–Marquardt method (Zakrzewski method): The Zakrzewski method estimates the centre using LMS method. The cost function of the Zakrzewski method, D_z, [1] is

$$D_\mathrm{z}(\alpha_\mathrm{z}, \beta_\mathrm{z}, \gamma_\mathrm{z}) = \sum_{l=1}^{L} \left|(s_{Il} - \alpha_\mathrm{z})^2 + (s_{Ql} - \beta_\mathrm{z})^2 - \gamma_\mathrm{z}^2\right|^2 \tag{5}$$

where s_{Il} and s_{Ql} are the I and Q components of lth data point, L is the number of data points, α_z and β_z are the I and Q components of the circle's centre, and γ_z is the radius of circle using the Zakrzewski method.

Centre estimation with dispersion minimisation (Hu method): The Hu method [6] minimises the dispersion of the fitted radius by minimising the cost function, D_h

$$D_\mathrm{h}(\alpha_\mathrm{h}, \beta_\mathrm{h}) = \sum_{l=1}^{L} (d_l - \mu)^2 \tag{6}$$

$$d_l = \sqrt{(s_{Il} - \alpha_\mathrm{h})^2 + (s_{Ql} - \beta_\mathrm{h})^2} \tag{7}$$

where α_h and β_h are the I and Q components of the centre of the circle, and μ is the mean of d_l. We use the LMS method with Levenberg–Marquardt method to minimise the cost function.

Numerical simulation setting: In this Letter, we conduct numerical simulations to investigate the performance of the methods introduced above. We conduct each simulation ten times using different seeds to generate random sequences of noise in each case. The phase rotation pattern is same as that used in [1]. The pattern $\phi(t)$ is given by

$$\phi(t) = A_\mathrm{p}\left\{1 - \sin^4\left(\frac{2\pi t}{T_0}\right)\right\} \tag{8}$$

where A_p is the range of phase rotation angle, and $T_0 = 2.0$ s is the period of the target motion. In the optimisation process, we use the average of the complex raw data as the initial value. For the Zakrzewski method, we use the true radius to initialise the value of γ_z.

Simulation results: We change the signal-to-noise ratio (SNR) from 10 to 60 dB and the range of the phase rotation angle from 15° to 180°. Fig. 1 shows the centre estimation error of the three methods. The solid and dotted lines show the results with the range of phase rotation angle of 30° and 90°, respectively. Fig. 2 shows the estimation results when we change the range of the phase rotation angle. The solid and dotted lines correspond to a SNR of 10 and 40 dB, respectively. The error is normalised to the signal intensity. As reported in [1], our results confirm that the Zakrzewski method outperforms the Park method. We note that the Hu method performs better than the two other methods, as shown in Figs. 1 and 2, even for a small range phase rotation angle and a low SNR. Fig. 3 illustrates one of our most challenging scenarios, with a phase rotation range as small as 15° and SNR of 40 dB. In this figure, the actual centre was at $(I, Q) = (2.0, 3.0)$. As shown, only the Hu method correctly estimates the centre position, indicating that static clutter can only be rejected with their method in this simulation.

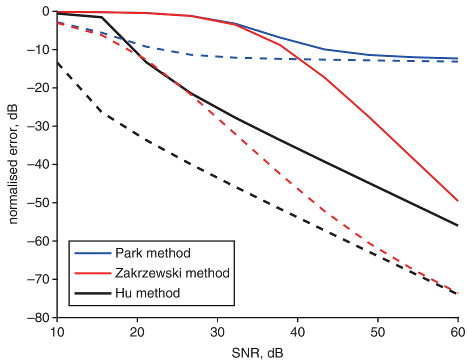

Fig. 1 *Estimated error using three methods. Phase rotation angle was 30° (solid line) and 90°(dotted line)*

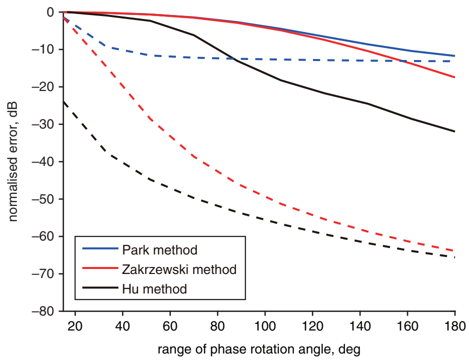

Fig. 2 *Estimated errors using three methods with a SNR of 10 dB (solid line) and 40 dB (dotted line)*

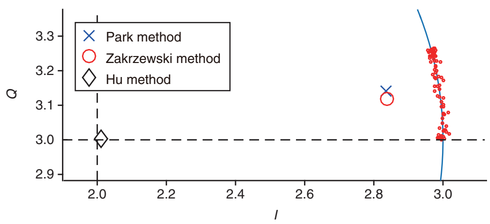

Fig. 3 *Estimated centres using three methods with phase rotation angle of 15° and SNR of 40 dB*

Discussion: Zakrzewski *et al.*, Park *et al.*, and Sakamoto *et al.* used a radar system operating at 10 GHz [1], 2.4 GHz [5], and 60 GHz [8], respectively. Given a displacement, a lower frequency generates a smaller phase rotation range. Thus, at lower frequency, clutter rejection is more difficult for all three methods.

One reason the Hu method outperforms the other two methods can be attributed to the number of variables: the Hu method only optimises two unknown variables, whereas the Zakrzewski method has three unknown variables.

Conclusion: The estimation of the circle's centre in the *I–Q* plane is required for the accurate measurement of vital signs. To estimate small displacements, an algorithm is required that is effective for small phase rotations. We compare three approaches using numerical simulations and conclude that the method proposed by Hu *et al.*, which minimises the variance of the data radius, has the best accuracy. Further, the Hu method performs well even with a phase rotation as small as 15°.

Acknowledgments: This research was partially supported by JSPS Grants-in-Aid (KAKENHI) numbers 15J05687, 25249057, 15K18077, and 15KK0243, Kyoto University SPIRITS Project, COI Program, and the R&D project for the expansion of radio spectrum resources for more efficient use of frequency resources for the future supported by the Ministry of Internal Affairs and Communications, Japan. This work was also partly supported by Hyogo Science and Technology Association.

Submitted: *29 April 2016* E-first: *25 July 2016*
doi: 10.1049/el.2016.1461
One or more of the Figures in this Letter are available in colour online.

S. Okumura, T. Sakamoto and T. Sato (*Graduate School of Informatics, Kyoto University, Yoshida-Honmachi, Sakyoku, Kyoto, Japan*)

✉ E-mail: sokumura@sato-lab.0t0.jp

M. Yoshioka, K. Inoue, T. Fukuda and H. Sakai (*Advanced Research Division, Panasonic Corporation, Hikaridai 3-4, Seika-cho, Souraku-gun, Kyoto, Japan*)

T. Sakamoto: Also with Graduate School of Engineering, University of Hyogo, 2167, Shosha, Himeji, Hyogo, Japan

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