

Matching Bistatic Target Responses in Radar Networks to Enable Vectorial Velocity Estimation

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Abstract— Multiple sensors in a radar network can be jointly evaluated to process the bistatic Doppler information of a target obtained under different aspect angles. This enables the estimation of the target’s vectorial velocity in a single snapshot. As a precursor to the joint evaluation, the monostatic and bistatic Doppler components need to be matched for each target in the range-Doppler map. In this work, a new approach for the target matching in the case of a radar-repeater network is presented. The matching is performed based on the correlation of monostatic and bistatic steering vectors extracted from the range-Doppler map for each receive channel of the radar. After validating the matched responses, the vectorial target velocity is determined. The approach is successfully tested with a 77 GHz radar and two repeaters by measurements of rotating cylinders.

Keywords — radar, repeater, radar network, multistatic radar, Doppler measurement, vectorial velocity.

I. INTRODUCTION

The next generation of radar systems will not only rely on the ever-increasing performance of single radar sensors but on multiple sensors in a radar network. This way, the performance in terms of crucial radar parameters like angle, range, and velocity resolution may be enhanced beyond the limitations of a single sensor. With widely distributed radar sensors a multi-perspective view on the targets is feasible, allowing for the extraction of the vectorial velocity of a target within a single measurement [1]. However, an issue of distributed radar sensors is the establishment of phase coherency, which may be solved by means of signal processing techniques [2], [3] but cannot achieve the same level of phase noise correlation [4] as a fully-coherent system.

An alternative way of building sensor networks is the so-called radar-repeater network [5], [6]. Here, both coherency and phase noise correlation are maintained without any need for clock synchronization or hardware links. In this type of network, the radar signal is relayed via repeater stations, and all the signal processing is done at the receiving radar node. With all processing performed only at the radar, the requirements on the repeater hardware are low, as only a power supply and a modulation signal for the built-in mixer need to be provided. The modulation within the repeater is essential to ensure the separability of the radar’s monostatic signal and the different bistatic signals provided by the repeaters. However, the modulated repeater signals will create bistatic peaks in the radar’s range-Doppler map which need to be matched to a corresponding monostatic target in order to make use of the measured bistatic Doppler information for this target.

In [1], to show the fundamental viability of vectorial velocity estimation in such a radar-repeater network, the bistatic targets were manually extracted and matched to the monostatic ones, which is time-consuming and error-prone.

In this paper, a method of automated matching of the monostatic and bistatic target responses based on the targets steering vectors is proposed. The Doppler information of the matched targets, which enables the vectorial target velocity estimation, is then checked for consistency before the actual estimation is carried out. In section II, the system model of the radar-repeater system is described. Next, the method for target matching and robust vectorial velocity estimation is described in section III. Finally, the proposed method is validated with measurements of rotating cylinders in section IV.

II. SYSTEM MODEL

In a radar-repeater network, the signal transmitted by the radar is reflected at the targets and subsequently received by the repeater. There, the received radar signal is modulated, amplified, and retransmitted. The retransmitted signal is then reflected again at the targets and received by the radar. Both monostatic and bistatic signals can then be processed at the radar simultaneously. Figure 1 shows the scenario for two repeaters in the network.

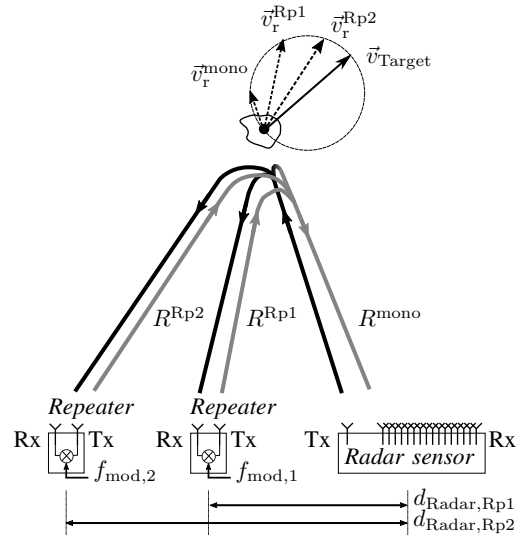


Fig. 1. The radar-repeater network illuminating an arbitrary target. The paths from the radar to the repeaters and back are drawn, as well as the radial velocities of radar and repeaters.

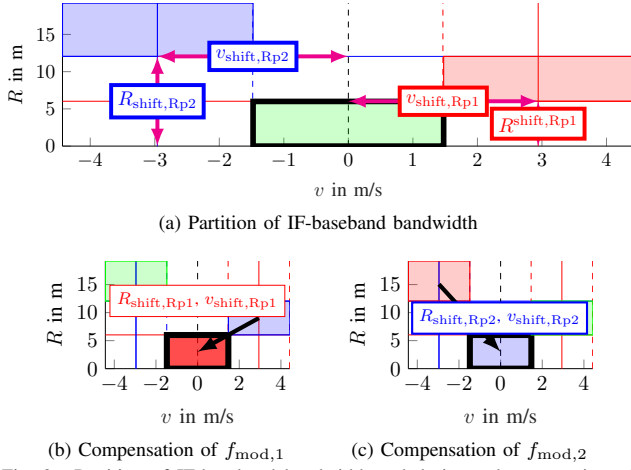


Fig. 2. Partition of IF-baseband bandwidth and designated monostatic and bistatic areas. After the modulation is removed, all target responses can be extracted in the areas marked with a black rectangle.

A. Signal Processing

A target's range and Doppler information is obtained for each receive channel of the radar via standard frequency modulated continuous wave (FMCW) radar processing, i.e. by calculating the two-dimensional fast Fourier transform (FFT) over all available samples and chirps of the receive signal. The bistatic repeater range and Doppler information can also be extracted this way, but the bistatic responses are shifted via the modulation of the repeaters to enable target separation. This shift can be compensated before further processing, leading to the range-Doppler maps of Fig. 2.

B. Target Separation in Range-Doppler Map

The repeater modulation adds a static offset in range and Doppler direction, which can be removed prior to further processing. If $s_{\text{IF}}[m, n]$ is the m th sample of the n th ramp of the receive signal, then

$$s_{\text{IF}}^{\text{bi}}[m, n] = s_{\text{IF}}[m, n] \cdot \exp(-j2\pi f_{\text{mod}}(m + n)), \quad (1)$$

$$m \in \{0, 1/f_s, \dots, (N_{\text{sample}} - 1)(1/f_s)\}$$

$$n \in \{0, T_r, \dots, (N_{\text{chirp}} - 1)T_r\}$$

is the time signal after compensating for the effect of the modulation for a repeater with modulation frequency f_{mod} ; T_r is the ramp repetition interval and f_s the baseband sampling frequency of the radar. The resulting time signal $s_{\text{IF}}^{\text{bi}}$ can then be processed identically to s_{IF} to yield the compensated bistatic range-Doppler plots of Fig. 2.

With this approach, a target list for the monostatic response as well as for both bistatic responses can be generated after 2D-FFT processing of the respective (compensated) time-signal and a subsequent constant false alarm rate (CFAR) detection and target extraction for all radar receive channels.

Both bistatic range and velocity are a superposition of the respective monostatic and bistatic component resulting in

$$R_{\text{Rp1/2}}^{\text{bi}} = R^{\text{mono}} + R^{\text{Rp1/2}} \quad (2)$$

$$\vec{v}_{\text{Rp1/2}}^{\text{bi}} = \vec{v}_r^{\text{mono}} + \vec{v}_r^{\text{Rp1/2}}. \quad (3)$$

Next, the matching of the monostatic and bistatic components for further processing is presented.

III. TARGET MATCHING

In this section, the novel target matching procedure based on the target receive phases is described.

A. Using the Monostatic DoA Information for Target Matching

The received signal phases over the antennas for a target depend on the angle-of-arrival of the signal reflected off that target. The steering vector $\vec{a}(\theta^{\text{mono}}) \in \mathbb{C}^{1 \times N_{\text{rx}}}$ for targets with any range or velocity observed under the angle θ^{mono} relative to the radar consists of the elements

$$\vec{a}_u(\theta^{\text{mono}}) = \hat{a}_u e^{jk d_u \sin(\theta^{\text{mono}})}, u = \{1, \dots, N_{\text{Rx}}\}, \quad (4)$$

where $k=2\pi f_c/c$ is the wave number, $\hat{a}_u$ the amplitude, and d_u describes the positions of the N_{rx} antenna receive elements. As shown by the gray lines in Fig. 1, the bistatic responses are received by the radar under the same angle $\theta_{\text{bi}}=\theta^{\text{mono}}$. Thus, for each bistatic response, there must be a bistatic range-Doppler bin (m, n) with a steering vector $\vec{a}^{\text{bi}}[m, n]$ similar to the monostatic steering vector $\vec{a}(R^{\text{mono}}, v_r^{\text{mono}})$ of a target at $R^{\text{mono}}, v_r^{\text{mono}}$. This information will be used to assign the bistatic target response to the monostatic one by correlating their steering vectors. The correlation is calculated as

$$\chi(m, n, R^{\text{mono}}, v_r^{\text{mono}}) = \frac{|\vec{a}(R^{\text{mono}}, v_r^{\text{mono}}) \cdot (\vec{a}^{\text{bi}}[m, n])^\dagger|}{\|\vec{a}(R^{\text{mono}}, v_r^{\text{mono}})\| \|\vec{a}^{\text{bi}}[m, n]\|}, \quad (5)$$

where $\|\cdot\|$ is the 2-norm and † is the Hermitian operator.

This way, the steering vector extracted from the monostatic target is correlated with all steering vectors from the range-Doppler bins in the region of the bistatic targets. This results in an ambiguity function [7] that shows the likeliness of a specific bistatic range-Doppler peak to be the matching response to the monostatic target under test. The result of this correlation is a value between 0 and 1, where 1 means the two steering vectors have exactly identical progressions and zero means some orthogonal steering vectors. In Fig. 3, the correlation of the phases for a target extracted at $R^{\text{mono}}=2.025$ m and $v_r^{\text{mono}}=0.223$ m/s is exemplarily shown with the monostatic and bistatic range-Doppler bins. By using the monostatic receive phases over the antennas to determine the monostatic target angle θ^{mono} , the position of the target is calculated. Subsequently, the bistatic range $R^{\text{Rp1/2}}$ from the target to the repeater is determined as distance between the estimated target position and the known repeater position. Then, the maximum correlation in the region of the bistatic range $R_{\text{Rp1/2}}^{\text{bi}}$ is determined and the bistatic target is assigned to the monostatic target under test.

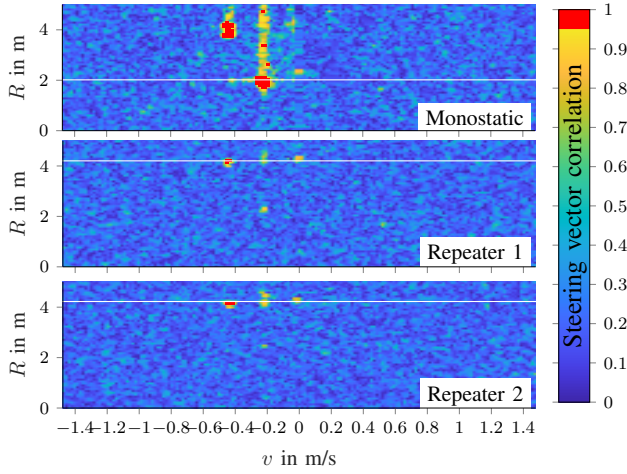


Fig. 3. Correlation of the monostatic phases of the target under test with phases of all monostatic (top) and bistatic (middle, bottom) range-Doppler bins. Values with a correlation higher than 0.95 are highlighted by red color. The monostatic/bistatic measured target range is drawn as a white line in each correlation plot.

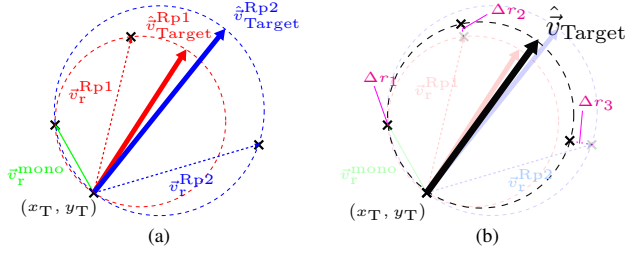


Fig. 4. First, the vectorial target velocity is estimated for each repeater separately as $\hat{v}_{Target}^{Rp1}$, $\hat{v}_{Target}^{Rp2}$ (a). If the two estimations deviate too much from each other, the vectorial velocity estimation is aborted, otherwise a LS estimation of $\hat{v}_{Target}$ minimizing $\sum_{i=1}^3 (\Delta r_i)^2$ including both repeaters is calculated (b).

B. Vectorial Velocity Estimation

After the monostatic and bistatic targets are assigned to each other, the vectorial velocity can be determined based on a circle defined by the radial velocities as described in [1]. For each repeater, an estimate of the vectorial velocity is then acquired, namely $\hat{v}_{Target}^{Rp1}$ and $\hat{v}_{Target}^{Rp2}$, see Fig. 4a. Those estimates are used to verify the match of both bistatic target peaks. If matched correctly, they should fulfill the conditions

$$1.5 < \frac{|\hat{v}_{Target}^{Rp1}| + |\hat{v}_{Target}^{Rp2}|}{\min(|\hat{v}_{Target}^{Rp1}|, |\hat{v}_{Target}^{Rp2}|)} < 3, \quad (6)$$

$$\langle \hat{v}_{Target}^{Rp1}, \hat{v}_{Target}^{Rp2} \rangle < 20^\circ, \quad (7)$$

where $\min(\cdot, \cdot)$ is the minimum between two values and $\langle \cdot, \cdot \rangle$ is the angle between the two vectors. The limits, which describe the allowed deviations of both estimates, are found heuristically. If the conditions are met, a least square (LS) estimation for the vectorial target velocity including $\hat{v}_r^{mono}$, $\hat{v}_{Target}^{Rp1}$, and $\hat{v}_{Target}^{Rp2}$ is calculated as $\hat{v}_{Target}$, see Fig. 4b.

Table 1. System parameters

Parameter		Value
Center frequency	f_c	77 GHz
Bandwidth	B	2 GHz
Chirp duration	T_c	200 μ s
Chirp repetition interval	T_r	220 μ s
Tx $\times$ Rx antennas	$N_{Tx} \times N_{Rx}$	1×16
Number of ADC samples per chirp	N_{sample}	512
Number of chirps	N_{chirp}	512
Modulation frequency repeater 1	$f_{mod,1}$	365.353 kHz
Modulation frequency repeater 2	$f_{mod,2}$	730.715 kHz
Horizontal distance repeater 1 to radar	$d_{Radar,Rp1}$	24 cm
Horizontal distance repeater 2 to radar	$d_{Radar,Rp2}$	69 cm
Cylinder diameter in measurement 1		6 cm
Cylinder diameter in measurement 2		1.6 cm

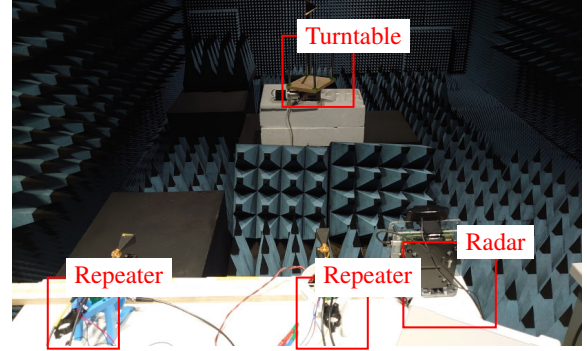


Fig. 5. Measurement setup consisting of a radar sensor with 16 receive antennas and two repeater elements placed in an anechoic chamber. The network is illuminating a rotating turntable at 2 m distance to the radar. Network and turntable are on the same height.

IV. MEASUREMENTS

Measurements in the anechoic chamber were carried out to evaluate the suitability of the approach.

A. Measurement Setup

For the measurements, a 1×16 FMCW radar is combined with two repeater elements. The chosen system parameters are described in Tab. 1. A picture of the measurement setup can be seen in Fig. 5. A turntable with two cylinders for the first measurement and four cylinders for the second measurement is placed at 2 m distance to the radar. The turntable rotates with an angular velocity of $40^\circ/\text{s}$ or 0.698 rad/s . Opposing metal cylinders on the turntable are placed 64 cm apart.

B. Measurement of Two Cylinders

A series of 50 measurements is evaluated with the introduced approach. In Fig. 6 the detected targets with their estimated vectorial velocity are shown for a selection of 12 of the 50 frames. Targets for which no vectorial velocity could be acquired and static targets are displayed without arrows indicating the velocity. Additionally, the absolute value and angle of the estimated target velocity are displayed in Fig. 7 for all 50 consecutive frames. In over 95 % the velocity estimation was successful with only a small deviation from the ground truth value of 22.34 cm/s . Also, the direction of the target is following the course expected from a target moving circularly.

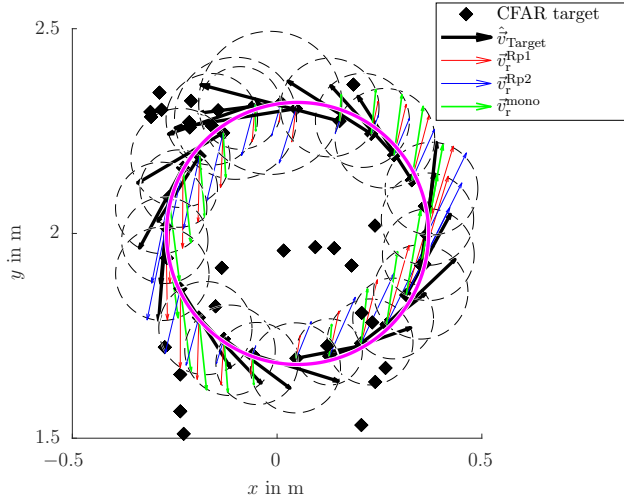


Fig. 6. Region of the xy -plot in which the turntable is positioned. Several consecutive measurement frames are superimposed to show the progress of the cylinder targets across the frames. All velocity components including the estimated vectorial target velocity $\hat{v}_{\text{Target}}$ are depicted as arrows. The pink circle shows the trajectory of the cylinder targets.

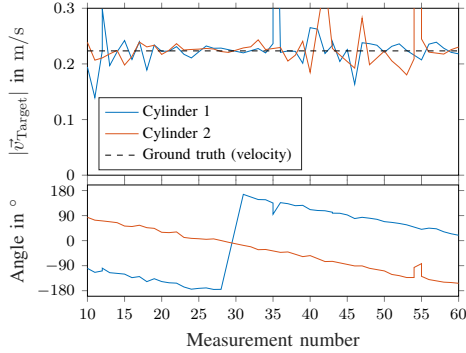


Fig. 7. The absolute value and the angle of the estimated vectorial target velocity plotted across multiple frames. As can be seen in the plots, the target velocity over the course of the measurements is estimated with low error.

C. Measurement of Four Cylinders

The second measurement is more demanding, as four cylinders are now placed on the turntable. In Fig. 8, an evaluated measurement frame is shown where both repeaters and the radar are able to detect all four targets. If the geometry prohibits the (bistatic) detection of targets, some targets may not be available for vectorial target detection. In that case, adding more repeaters may remedy the situation. As for the evaluated frame in Fig. 8, it is possible to match the bistatic targets using the new matching approach, as the monostatic and bistatic targets are detectable in the range-Doppler map. This demonstrates that the vectorial velocity can be acquired even if the measurement conditions in terms of separability by target range and angle are more challenging.

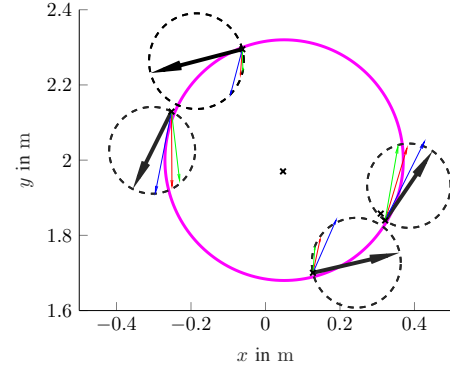


Fig. 8. Rotating table with four cylinders mounted on top. The reconstructed vectorial target velocity as well as all separate velocity components can be seen. The trajectory of the cylinders is drawn as pink circle.

V. CONCLUSION

With the signal processing proposed in this work, the matching between monostatic and bistatic targets for vectorial velocity estimation in a radar repeater network can be provided automatically. The matching based on the target steering vectors and the measured bistatic range is described, and subsequent measurements prove that the target matching works in a reliable way and can be used to programmatically combine the monostatic and bistatic measured Doppler information of targets. Moreover, invalid matches are suppressed by checking for consistency between the velocities obtained from different bistatic responses. The method can be easily adapted to more repeaters to further enhance the reliability of the estimation. Thus, the proposed method works in a straight-forward and robust way to fully automate the estimation of vectorial velocities for multiple targets and can potentially be used in various applications.

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