Vibrometry and Sound Reproduction of Acoustic Sources on Moving Platforms Using Millimeter Wave Pulse-Doppler Radar

CHRISTOPHER T. RODENBECK\textsuperscript{1}, (Senior Member, IEEE), JOSHUA B. BEUN\textsuperscript{1}, RAGHU G. RAJ\textsuperscript{1}, (Senior Member, IEEE), AND RONALD D. LIPPS\textsuperscript{2}

\textsuperscript{1}U.S. Naval Research Laboratory, Washington, DC 20375-5307, USA
\textsuperscript{2}U.S. Naval Research Laboratory, Washington, DC 20375-5307, USA (Retired)

Corresponding author: Christopher T. Rodenbeck (chris.rodenbeck@ieee.org)

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ABSTRACT
This paper presents millimeter wave (MMW) pulse-Doppler radar for the remote sensing of acoustic vibration for targets in motion. A key advance in this work is the development of precision motion compensation for MMW vibrometry, making it possible for a monostatic radar to extract and reproduce small-scale vibrations on platforms undergoing large-scale motion. The motion compensation methodology uses a hierarchical approach combining direct and indirect estimation for the time dependent variation of target motion parameters across coherent samples in radar fast time and slow time. Additionally, the wide bandwidth commonly available at MMW allows vibrations to be selectively detected and disambiguated in range across the length of moving targets. Stretch processing compresses the received radar bandwidth by more than 10x, so that Hilbert sampling can be used to acquire quadrature samples using a single analog-to-digital converter. The resulting complex baseband response directly reproduces the target’s acoustic signature. To demonstrate the technique, a 94 GHz pulsed linear frequency modulated (LFM) radar accurately reproduces the pitch of audio waveforms generated by a speaker in the rear of an accelerating automobile at an outdoor test range. These results should have major consequences for the development of MMW vibrometry as a remote sensing technique.

INDEX TERMS
Millimeter wave radar, vibrometry, pulse-Doppler radar, motion compensation, audio recording, sound reproduction, acoustic measurements.

I. INTRODUCTION
Doppler radar provides an alternative to conventional techniques (e.g., accelerometers, lasers, microphones) for sensing small-scale vibrations. Predominant applications include the detection of vital signs [1]–[14], sound and speech [14]–[29], and structural vibration [30]–[38]. Considerable recent attention is directed at MMW vibrometry [15], [37]–[45] due to the widespread commercial availability of compact wideband transceivers at frequencies > 60 GHz. Demonstrations are typically continuous wave (CW) at target distances ranging from a few millimeters to several meters [1]–[45].

Airborne synthetic aperture radar (SAR) [46]–[52] systems also show capability to observe the vibration of loitering targets as distortion to the radar image, implying potential to extend radar vibrometry to remote sensing applications given the maturation of techniques for accurate extraction and analysis of the vibration in real-world environments.

Unfortunately, progress in Doppler vibrometry faces major limitations [53] when it comes to the ability to sense the small-scale vibration of targets in motion. Radar sound/vibration reproduction results to-date require the targets under investigation to be conspicuously still [1]–[45], [45]–[53]. Although limited cyclic motion can be canceled at close range under constrained conditions using interferometric and multistatic techniques [54]–[61], such approaches greatly increase in cost and complexity for observation at longer standoff. Recent demonstrations introducing the capability to track people in motion implicitly require the subjects to come to rest in order to detect and interpret vital signs [53], or else simply detect the presence of vibration without the ability to analytically reconstruct it [4], [62]. Airborne motion
compensation techniques leveraging on-board inertial measurement and/or global navigation sensors [46]–[51], [63] can correct for the dynamics of the interrogating radar but not for the dynamics of the target. Widespread micro-Doppler techniques [64]–[66] provide a useful time-frequency methodology for analyzing and separating components of cyclic motion superimposed on bulk target motion (e.g., the analysis of human gait, gestures, rotor blades, bird flight, boat dynamics, etc.), but the superposition of multiple sources of motion remains a difficult issue [64], [69]–[74]; a radar demonstration of small-scale vibrometry and sound reproduction for targets in large scale motion is lacking.

To overcome this challenge, this paper presents a hierarchical motion compensation approach extending traditional techniques [75], [76] from SAR to solve the difficult problem of analyzing vibration from moving targets at MMW. Importantly, several coarse estimation steps are introduced to pre-condition the MMW data set for increasingly refined stages of motion compensation. The robustness and performance of this approach are demonstrated experimentally. A 94 GHz pulse-Doppler LFM radar operating at an outdoor test range is used to interrogate a moving acoustic source. The resulting complex data set is coherently processed, with application of the hierarchical motion compensation routine, to remove the effects of linear and nonlinear target motion so that the range-Doppler map retains only vibration information in the Doppler dimension. Vibration and sound waveforms are thus selectively reproduced at specific ranges directly from the radar baseband waveform, without the need for additional complex analysis or audio processing. These results significantly expand the applications of radar vibrometry, eliminating the present limitations due to target motion.

This paper is organized as follows: Section 2 describes key principles of MMW vibrometry for both stationary and moving targets. Section 3 details a hierarchical MMW motion compensation approach blending direct and indirect estimation techniques for the time dependent variation of target motion parameters across coherent radar samples in radar fast time and slow time. Section 4 describes the MMW test range and instrumentation developed for the experimental demonstrations in this paper. The design parameters of this system are well within the permitted capabilities of commercial W band automotive radar, but with enhanced flexibility in the digital processing and memory length. Section 5 presents results for detecting and reproducing audio waveforms from an automotive target undergoing complex motion. Section 6 concludes the paper.

II. MMW PULSE DOPPLER VIBROMETRY

The round trip phase delay between a radar and its target is $e^{j4\pi f_v t}$ where $r$ is the instantaneous range and $\lambda$ is the radar wavelength. Target vibration in range modulates this phase delay, allowing the radar to act as a remote vibration transducer.

Fig. 1 illustrates a stationary but vibrating target observed by a radar transceiver. Approximating this target as a point scatterer vibrating sinusoidally at a rate $f_v$ with peak vector displacement $\bar{D}_v$, the maximum target deflection observed by the radar is $\Delta r = \bar{u}_r \cdot \bar{D}_v$ where $\bar{u}_r$ is the unit vector along the radar line of sight. The target’s peak sinusoidal vibration in range $\Delta r$ modulates the round trip phase delay $e^{j4\pi f_v t}$ of the radar return so that the complex baseband envelope of the received signal can be expressed as a function of time $t$ as

$$\tilde{s}_{RX}(t) = A_c e^{j4\pi \Delta r \sin(2\pi f_v t)}$$

(1)

where $A_c$ is the received carrier amplitude. From classical analog communication theory [81], the sinusoidally modulated phase delay of (1) can be decomposed into Bessel harmonics so that

$$\tilde{s}_{RX}(t) = A_c \sum_{n=-\infty}^{\infty} J_n \left( \frac{4\pi}{\lambda} \Delta r \right) e^{2j\pi nf_v t}$$

(2)

where $J_n(\cdot)$ is a Bessel function of the first kind of order $n$.

The received waveform thus consists of an infinite series of positive and negative harmonics spaced $f_v$ apart around the carrier. To illustrate this fact, Fig. 2 uses the MMW radar system described in this paper to observe a stationary vibrating 125 Hz tuning fork. The baseband spectrum clearly shows Bessel harmonics spaced at $125 \text{ Hz}$. 

The advantages of MMW pulse Doppler radar for vibrometry become clear in an analysis of sinusoidal vibration in range-Doppler space. As shown in Fig. 3, the received “fast
time” samples recorded within each radar pulse represent the target return vs. range, with range resolution \( \Delta R = \lambda / (2 \cdot BW_{f_{\text{rad}}}) \) where \( BW_{f_{\text{rad}}} \) is the radar’s fractional bandwidth. The fast Fourier transform (FFT) across radar samples recorded at a specific range delay represents the “slow time” Doppler spectral response at that range. Doppler resolution is \( \Delta f = \text{PRF} / N_{\text{pulses}} \) where \( \text{PRF} \) is the pulse repetition frequency and \( N_{\text{pulses}} \) is the number of pulses observed. The total noise power per range-Doppler cell is proportional to the cell size \( \Delta R \cdot \Delta f \), and the amplitude of the strongest baseband harmonic of vibration is proportional to \( J_1 \left( 4\pi \Delta r / \lambda \right) \). Since both the signal strength and noise power are functions of frequency/wavelength, MMW operation can significantly enhance sensitivity to acoustic vibration. For example, for a 25.4-μm vibration observed with 10% fractional bandwidth, increasing the carrier frequency from 1 GHz to 100 GHz increases SNR by 24 dB. Beyond sensitivity, improved range resolution \( \Delta R \) is an additional advantage to performing vibrometry at MMW. For Doppler radars operating CW or with large \( \Delta R \), multiple sources of vibration within a scene or along an extended target must superimpose upon one another; separating superimposed audio signals is computationally challenging and a longstanding subject of research [66]–[74]. With the improved range resolution available at MMW, individual sources of vibration can be localized in range.

Despite these advantages, the issue of platform motion constitutes a major technical challenge at MMW. Consider the extended target shown in Fig. 4. For each received pulse, the radar return vs. range, or “pulse profile”, can be approximated as

\[
s_{\text{RX}} (m) = \sum_{m} \rho \delta (m \cdot \Delta R - r_m)e^{j \frac{2\pi}{\lambda} \left( r_m + \Delta r_m \sin(2\pi f_v t) \right)}
\]

where for the \( m \)-th range cell: \( r_m \) is the range, \( \Delta r_m \) is the peak vibration along the radar line of sight, \( f_v \) is the vibration rate, and \( \rho \) is the complex reflectivity. For a moving target, \( r_m \) can be expressed as a function of time

\[
r_m (t) = r_{\text{o},m} + \left[ \mathbf{v} (t) \cdot t + \mathbf{a} (t) \cdot t^2 \right] \cdot \mathbf{u}_r.
\]

where \( r_{\text{o},m} \) is the starting range and \( \mathbf{v} (t), \mathbf{a} (t) \) are the platform’s velocity and acceleration, respectively. The effect of platform motion \( f_v (t) \) displaces both the position in range \( \delta (m \cdot \Delta R - r_m) \) and the phase response \( e^{j 2\pi f_v (t) t} \) vs. time. Extracting the instantaneous frequency \( f_v (t) \) of a small-scale vibration requires compensation for these effects in both range and phase. Since the phase term in III is at the wavelength scale, motion compensation can be especially challenging at MMW. The hierarchical motion compensation approach presented in the following section meets this challenge to achieve highly accurate MMW measurement of vibration on moving platforms.

III. MOTION COMPENSATION

To provide robust motion compensation for MMW data sets, this paper presents a novel hierarchical approach blending direct and indirect estimation in both range and phase. The novelty of this hierarchical approach lies in the specific manner in which the range alignment and phase compensation are steps formulated and implemented so that each stage of motion compensation improves the estimate for the succeeding stage, increasing the quality and overall resilience of the process at MMW. Motion compensation in range, or “range alignment”, operates in fast time, beginning with a direct estimate for the target motion parameters [75], followed by an indirect estimate that refines the same parameters using entropy optimization [77]. This is followed by motion compensation in phase, or “phase compensation”, which operates in slow time on the range-aligned data set, beginning with an indirect estimate for quadratic phase error based on entropy optimization, followed by a phase gradient autofocus (PGA) [76] process to account for higher-order phase errors. Techniques specialized for airborne operation [75], [76] (e.g., keystone processing, range migration algorithms, and polar format processing, etc.) are not required for analysis of
the experimental data used in this paper and are therefore not considered.

To constrain the computational resources required, this paper performs motion compensation over finite intervals/frames of consideration that can be concatenated for subsequent analysis or extended reproduction. For the automotive targets used in this demonstration, 1 s motion compensation intervals provide good results.

A. RANGE ALIGNMENT

The range alignment process presented here begins with a pulse-by-pulse search for the time delay \( \tau \) that maximizes the correlation between the \( i \)th pulse profile and a reference pulse, as illustrated in Fig. 5. As a novel subtlety introduced in this paper, the reference pulse used in this time-domain correlation is a composite of all prior pulse profiles, each shifted by its calculated delay, and accumulated in a recursive filter using a weighting coefficient of 0.4 for the most recent \((i-1)\)th pulse and 0.6 for all previous pulses. This recursive filter reduces the effect of MMW target scintillation, thus increasing the robustness of this initial stage of motion compensation to nonidealities in the radar data. Fitting a 2nd order polynomial to the resulting delay vector \( \mathbf{\tau} \) provides an estimate of a constant velocity \( v_r = \ddot{v} \cdot \mathbf{u}_r \), along the radar line of sight over the interval of consideration.

Using the above direct procedure, the error in the range alignment across pulses is ideally \( < 0.5 \Delta R \). To further refine this estimate, the aligned return from every \( n \)th pulse is next time shifted according to the motion model defined by the directly obtained estimates for \( v_r \) and \( \dot{v}_r \); the selected pulses are then summed into an accumulated pulse profile. Calculating the 1-D entropy [76] of this accumulated profile provides a measure of its sharpness, with minimum entropy corresponding to maximum sharpness. Optimizing first \( v_r \) and then \( \dot{v}_r \) to minimize entropy provides an updated estimate for their values; this entropy optimization is then iterated on an updated accumulated pulse profile until a stable solution for \( v_r \) and then \( \dot{v}_r \) is reached. The complete data set is then aligned in range based on the final values for \( v_r \) and \( \dot{v}_r \).

Throughout the range alignment process, time shifting is accomplished by converting the pulse profile to the frequency domain (i.e., a fast time FFT for each pulse), multiplying by a phase ramp \( e^{-j2\pi f \tau} \), corresponding to the time delay, and then performing an inverse FFT. This method allows sub-range bin shifts in the data.

B. PHASE COMPENSATION

The range alignment procedure described above manipulates the fast time pulse profiles and therefore operates at the range resolution scale \( \Delta R \) rather than the wavelength scale \( \lambda \). Thus, although range alignment can compensate effectively for the amplitude distortion term \( \delta [m \cdot \Delta R - r_m(t)] \) in III, significant errors remain in the phase response \( e^{j2\pi r_m(t)\beta} \). As an initial step in the phase compensation process, this paper introduces an indirect estimate for the quadratic phase error. The range aligned data set is converted to a range-Doppler map, such as illustrated in Fig. 3, by applying an FFT across the slow time dimension. A simple quadratic phase of

\[
\varphi_n = \alpha \cdot \left( n - \frac{N_{\text{pulses}}}{2} \right)^2, \quad n = 0 \ldots N_{\text{pulses}}
\]  

is applied across the Doppler dimension where \( \alpha \) is a scale factor. Optimizing \( \alpha \) over 40 iterations to minimize the 2-D entropy of the range-Doppler map eliminates gross quadratic phase errors.

Finally, PGA [76] is used to refine the phase error estimate based on a measurement of the differential phase error across a selection of prominent scatterers in range-Doppler space. PGA is a direct estimation technique operating on the measured data that, unlike the prior motion compensation steps, is unconstrained by any particular motion model and can compensate for residual higher order phase errors, including errors due to distributed scattering from the target’s underlying structure. The results in this paper use five iterations of PGA to correct for residual phase error in range-Doppler maps processed over each 1 s frame of target motion.

IV. MMW AUTOMOTIVE TEST RANGE

To demonstrate the proposed approach, an acoustic source on a moving platform is interrogated at an outdoor MMW test range. Fig. 6 shows the 94 GHz pulse-Doppler radar developed for this experiment using instrumentation and commercially available components. The 4 GHz bandwidth and 80 mW average transmit power of this experimental setup are within the permissible performance envelope of commercial W band automotive radar [78], but with enhanced flexibility for customized digital processing and extended memory length when compared with off-the-shelf short range MMW radar systems.

Excluding the Tektronix 7000A arbitrary waveform generator (AWG) and 10 MHz rubidium stable local oscillator (STALO), the system is built using WR-10 rectangular waveguide and coaxial connectorized components, with a
FIGURE 6. MMW pulse-Doppler radar system developed for the experiments in this paper. The transmitter outputs an LFM pulse of 4 GHz bandwidth, with an average transmit power of 80 mW. The 7.5-dB-noise-figure receiver deramps the received pulse to an IF center frequency of 100 MHz.

As illustrated in the figure, the STALO provides a timing reference to the AWG and phase locked oscillator (PLO). The PLO output at 14.5 GHz output splits between the transmitter (TX) and receiver (RX) and separately multiplies 6x to 89 GHz in both in order to maintain high TX to RX isolation.

In the TX, the 6x multiply stage has sufficient gain to allow the 89 GHz tone to upconvert a 4-GHz-bandwidth LFM pulse from the AWG to the 92-96 GHz range, using an image reject (IR) high pass filter (HPF), bandpass filter (BPF), and low pass filter (LPF) to suppress undesired frequency content. The pulse width is 100 µs and the PRF is 4 kHz. The peak transmit power within the pulse is 200 mW.

Both TX and RX antennas are vertically polarized with an 11° beam width and 23 dB gain. In the RX, a front end switch protects a low noise amplifier (LNA) during the transmit pulse. The RX achieves an overall noise figure of 7.5 dB. The RX frequency conversion plan that mirrors the TX in order to downconvert and “deramp” the received 92-96 LFM pulse to an IF center frequency of 100 MHz. This deramping approach, also known as “stretch processing” [79], collapses the radar bandwidth to effectively implement pulse compression in the analog domain by multiplying the two offset frequency ramps in the receiver. An IF bandwidth of 9 MHz defines a usable range swath of 20 m that matches the length of the test range. The IF output of Fig. 6 is digitized by a Spectrum Instrumentation Corporation DN2.225-08 NETBOX 8-bit digitizer at a sample rate of 312.5 MHz and maximum record length of approximately 4 s. Complex (i.e., quadrature or digital IQ) samples are generated digitally using Hilbert sampling [80] to eliminate the need for the quadrature ADCs and IQ calibration typically used in radar vibrometry [9]. Coherent processing over 4096 pulses provides 36 dB processing gain to a calibration target.

As described in Section 3, the first step in compensating for the target’s motion is a two-stage range alignment process operating in radar fast time. Fig. 9 shows the pulse profile vs. range before and after range alignment for every eighth received pulse. The second step in motion compensation is a two-stage phase alignment process needed to remove phase errors in radar slow time. Fig. 10 illustrates the resulting

FIGURE 7. The moving platform used for this demonstration is (a) an automobile that accelerates from a stop to a typical velocity of 3.5 m/s (10 mph) over the 20 m test range. A speaker mounted in the open cargo area is the acoustic source, with peak sinusoidal displacement of 120 µm at 100 Hz decreasing monotonically to 8 µm at 500 Hz.

MTI Instruments Microtrak 4 laser vibrometer, is uniform along the surface of the speaker cone, monotonically decreasing in amplitude from 120 µm at 100 Hz to 8 µm at 500 Hz. This acoustic range corresponds to the range of audio stimuli used in the experimental demonstration of the following section.

V. EXPERIMENTAL RESULTS

In the first test run, the speaker is mounted in the automobile’s open cargo area, vibrating at 150 Hz with a peak sinusoidal displacement of 105 µm. While illuminated by the MMW pulse Doppler radar, the vehicle traverses the 20 m test range under human control with an initial velocity of 0.5 m/s and acceleration of 1.1 m/s² and an initial distance of 1.6 m. The range waterfall plot shown in Fig. 8 illustrates the progression in time of radar’s received SNR vs. range delay, without the application of motion compensation processing.

FIGURE 8. Range waterfall plot illustrating received SNR vs. elapsed time and range for the automobile traversing the 20 m test range. The speaker shown in Fig. 7 is vibrating at 150 Hz with a peak sinusoidal displacement of 105 µm.

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cascade of pulse profiles vs. radar slow time after application of range alignment and phase compensation. The motion compensated response vs. time appears effectively immobile, as if the target were a stationary platform at a fixed range whose SNR degrades over time.

Range-Doppler maps, as described in Section 2, provide a more meaningful tool than range waterfall plots for visualizing the target’s acoustic signature. Fig. 11 shows the range-Doppler map for the radar data set of Fig. 8, before the application of motion compensation; the acoustic signature is obscured by the target’s large scale motion. Fig. 12 shows the same data set after the application of motion compensation and zoomed in to a range extent corresponding to the size of the vehicle. In this case Doppler harmonics show up clearly at 150 Hz intervals corresponding to the 150 Hz tone transmitted by the speaker.

Fig. 13 plots the magnitude of the radar’s complex baseband power spectrum at the range of maximum Doppler variance. The 150 Hz tones and 18 higher order harmonics are consistent with the response of an ideal stationary phase modulator described in Section 2. The audio reconstructed from the baseband radar spectrum agrees well with the audio file transmitted from the moving speaker. Background acoustic noise (scaled by the relative radar reflectivity of the acoustic sources) is also apparent at the same range delay as the speaker. The signal-to-noise ratio at the fundamental harmonic of vibration exceeds 43 dB, which is consistent with a degradation of the 16 bit audio to 8 effective bits corresponding to the radar 8 bit digitizer’s dynamic range. Importantly, this demonstration and all following results in this paper use no audio filtering or other baseband processing to intentionally enhance the received radar data.

Additional moving tests repeat the preceding scenario while incrementing the audio tone from 100 to 500 Hz in 50 Hz intervals for each experiment. After motion compensation, the baseband radar power spectrum shows a fundamental tone and associated harmonics at intervals corresponding to the speaker’s vibration, as shown in the single-sided power spectrum of Fig. 14. A composite audio file based on received radar data from all nine experiments shows good agreement with the original acoustic transmission.
FIGURE 13. (a) Magnitude of the complex power spectrum at the range of maximum Doppler variance from Fig. 12. (b) The audio file transmitted from the speaker. (c) The audio received by the radar system, including background noise from other acoustic signatures at that range delay.

FIGURE 14. (a) Received motion-compensated power spectra for 9 automotive test runs in which the speaker vibrates at peak sinusoidal amplitudes ranging from 120 $\mu$m at 100 Hz to 8 $\mu$m at 500 Hz. (b) A composite audio file of the tones transmitted by the speaker. (c) A composite audio file of the sound captured by the radar.

FIGURE 15. Range-Doppler map for an automotive test run in which the speaker transmits a 100-235 Hz chirp. Peak sinusoidal vibration varies from 120 $\mu$m to 50 $\mu$m over this range.

FIGURE 16. Motion compensated range-Doppler map for the test run shown in Fig. 15. The acoustic response has a more complex structure in comparison to the single tone test in Fig. 12.

To demonstrate the effectiveness of this motion compensation technique using a more complex audio waveform, an additional moving test repeats the preceding experiment for the case in which the audio waveform is a periodic triangular FM chirp swept from 100 to 236 Hz at a rate of $\pm 136$ Hz/s. Peak sinusoidal displacement of the speaker varies monotonically from 120 $\mu$m to 50 $\mu$m over this range. As illustrated in the range-Doppler map of Fig. 15, the platform motion is highly nonlinear. Fig. 16 shows the same test result after the application of motion compensation. In this case, the acoustic response in Doppler space has greater complexity in comparison to the single tone result of Fig. 12. Fig. 17 again plots the magnitude of the complex radar baseband power spectrum at the range of maximum Doppler variance. Although the cross modulation property of phase modulation [81] tends to obscure the received signal’s FM chirp structure, the audio signal reconstructed by radar agrees well with the speaker’s original audio transmission. For this experiment, alternative graphical techniques are useful for analyzing and identifying the received audio signature. As shown in Fig. 18, using the short-time Fourier transform [82] to plot the magnitude of the radar’s baseband power spectrum vs. time clearly illustrates the FM chirp structure transmitted by the speaker. In addition, the cepstrum transform [83] applied to the same data set can be used to plot the instantaneous baseband frequency vs. time, reproducing the original acoustic signal with excellent fidelity.
the vibrometry and sound reproduction of acoustic sources on moving platforms. A hierarchical motion compensation technique blends direct and indirect estimation in radar fast time and slow time to align coherent pulses in range and phase so that the resulting complex baseband response accurately reproduces acoustic vibration at selected locations along a moving platform. Experimental results are obtained using a speaker as an acoustic source in the rear of an automobile as it accelerates across a monostatic MMW radar test range. Motion-compensated pulse-Doppler radar data reproduce the target’s acoustic signature with high fidelity in a series of experimental demonstrations.

Radar systems customized for this application, with enhanced transmit power and improved angular resolution, should be able to extend the operational range of this MMW technique, making it possible to add a new dimension of sound reproduction to conventional SAR images. The results have major consequences for MMW vibrometry as a remote sensing technique.

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JOSHUA B. BEUN received the M.S. and Ph.D. degrees in physics from North Carolina State University, in 2004 and 2008, respectively. Since then, he has been with the U.S. Navy Research Laboratory, Washington, DC, where he is currently a Research Physicist with the Advanced Concepts Group, Radar Division.

RAGHU G. RAJ (Senior Member, IEEE) received the Ph.D. degree in electrical engineering from The University of Texas at Austin, in 2007. He is currently a Senior Research Scientist and the Head of the Radar Imaging and Target ID Section, Radar Division, U.S. Naval Research Laboratory (NRL), Washington, DC, where he leads the research and development of advanced methods in statistical signal processing and machine learning with applications to various U.S. DoD funded programs.

He has over 50 publications in various international journals, conferences, and technical reports. He holds six U.S. patents. His research interests span various signal/image processing and machine learning problems in radar and remote sensing. He was a recipient of the one NRL Alan Berman Publication Award.

RONALD D. LIPPS. photograph and biography not available at the time of publication.