ARL-TR-10087 ● Apr 2025

Nonlinear Radar for Finding RF Electronics: A Review of Relevant Literature, 2017–2024

by Gregory Mazzaro, Kyle Gallagher, Alex Bouvy, and Kelly Sherbondy

NOTICES

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Gregory Mazzaro
The Citadel, The Military College of South Carolina

Kyle Gallagher, Alex Bouvy, and Kelly Sherbondy
DEVCOM Army Research Laboratory

REPORT DOCUMENTATION PAGE

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED START DATE	3. DATES COVERED END DATE
April 2025	Technical Report	1 November 2024	14 March 2025

4. TITLE AND SUBTITLE
Nonlinear Radar for Finding RF Electronics: A Review of Relevant Literature, 2017–2024

5a. CONTRACT NUMBER	5b. GRANT NUMBER	5c. PROGRAM ELEMENT NUMBER
5d. PROJECT NUMBER	**5e. TASK NUMBER**	**5f. WORK UNIT NUMBER**

6. AUTHOR(S)
Gregory Mazzaro, Kyle Gallagher, Alex Bouvy, and Kelly Sherbondy

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
DEVCOM Army Research Laboratory ATTN: FCDD-RLA-LC Adelphi, MD 20783-1138	ARL-TR-10087

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.

13. SUPPLEMENTARY NOTES
ORCID: Gregory Mazzaro, 0000-0001-5814-7425

14. ABSTRACT
A review of publicly available literature relevant to nonlinear radar is conducted. This review discusses mathematical modeling of nonlinear interactions, applications for this type of radar, capabilities of modern nonlinear-radar systems, and common architectures for those systems. This document extends and updates the authors' archive of nonlinear-radar research and its intended readership are the engineers who might advance the state of the art in nonlinear-radar technology.

15. SUBJECT TERMS
Photonics, Electronics, and Quantum Sciences; radar; nonlinear; junction; harmonic; detection; electronic

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	C. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UU	34

19a. NAME OF RESPONSIBLE PERSON	19b. PHONE NUMBER *(Include area code)*
Gregory Mazzaro	(520) 691-6300

STANDARD FORM 298 (REV. 5/2020)
Prescribed by ANSI Std. Z39.18

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Acknowledgments

This report marks the end of nearly 18 years of research conducted by Dr. Gregory ("Greg") Mazzaro in support of ARL's mission.

Dr. Mazzaro began his work at ARL's Adelphi Laboratory Center (ALC) on June 4, 2007, as a graduate-student intern; he was hired under the Summer Temporary Employment Program (STEP) while he earned his doctorate at North Carolina State University. Dr. Mazzaro completed his degree requirements in November 2009 and returned to ALC in December to work full-time as an electronics engineer. He joined the Hardware Team where he primarily participated in field tests of the Synchronous Impulse Reconstruction Radar, developed a ring-resonator-based technique for measuring electric-permittivity of sands and soils in situ, and advanced NLR technology for detecting RF electronics.

In July 2013, Dr. Mazzaro left ARL, and in August 2013, he began a tenure-track professorship at The Citadel in Charleston, South Carolina. In the summer of 2014, Dr. Mazzaro returned to ARL at ALC as an engineering consultant under a contract between General Technical Services, LLC (GTS) and ARL to advance the Army's ultra-wideband and NLR technology. Since 2014, Dr. Mazzaro has consulted for ARL through GTS.

Dr. Mazzaro's part-time consulting agreement ended on March 27, 2025. Between late 2009 and early 2025, to document their radar-related advancements, Dr. Mazzaro and his ARL collaborators authored 9 journal manuscripts, 54 conference-proceedings papers, and 31 technical reports.

For the support that his coworkers have given him over the past 18 years, Dr. Mazzaro would like to thank the following individuals:

- Karl Kappra, for hiring Greg as a "temp" into the RF Branch in 2007 and as a full-time civilian employee in 2009,
- Marc Ressler, for sharing his extensive technical expertise—teaching Greg how to speak and to think like a radar engineer,
- Gregory Smith, Francois Koenig, and Getachew Kirose, for teaching Greg how to operate, maintain, and upgrade radar systems,
- Kenneth Ranney, for guiding Greg as a STEP intern, introducing him to SPIE, and encouraging him to patent his work,

- Nadine Loman and ARL's Intellectual Property Office, for helping Greg and his teammates secure 10 patents,
- Traian Dogaru, David Vance, Brian Stanton, Lam Nguyen, Anders Sullivan, and Calvin Le, for collaborating with Greg on a wide variety of projects,
- Kyle Gallagher, Brian Phelan, Alex Bouvy, Colin Kelly, Benjamin Kirk, and Khalid Salik, for continuing to advance (ultra-wideband and nonlinear) radar technology,
- David McNamara and Anthony Martone, for nearly two decades of friendship, and
- Kelly Sherbondy, for playing so many different roles in Greg's life—team lead, supervisor, mentor, friend, brother—with positivity, grace, strength, humility, and abundant laughter.

1. Introduction

This report serves as an extension and an update of a previous literature review conducted by the authors.[1] That earlier review surveyed all articles related to nonlinear radar (NLR) for finding RF electronics, publicly available and published before 2017. Another group of authors added to this summary of NLR literature in 2021.[2] Follow-on reviews in 2021 and 2023 focused on passive harmonic RF identification (RFID) systems[3] and nonlinear tags.[4]

The review provided in this report summarizes all publicly available NLR literature published between 2017 and 2024. In some instances, rather than cite multiple similar papers published by a single set of authors, one representative paper (typically the latest one) was selected for inclusion in this document. One goal of this review is to highlight the accomplishments of all groups conducting research on (or directly relevant to) NLR, such that all parties interested in conducting similar research might be aware of each other's work. The primary goal of this review, however, is to provide a summary archive of NLR research for a new generation of engineers who might build on this research and greatly advance the state of the art of NLR.

2. NLR Concept and its Applications

The concept of NLR is depicted in Figure 1.

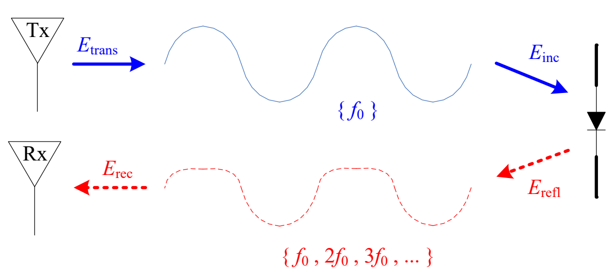

Figure 1. NLR concept.

A radar transmit (Tx) antenna emits a wave—with an electric field denoted by E_{trans}—carrying a known frequency (e.g., f_0) toward the nonlinear target. Upon reaching the target, the wave—with an e-field denoted by E_{inc}—is incident upon the target. The nonlinear target is illustrated as a diode with wire leads for its "antennas." A new wave—with an e-field denoted by E_{refl}—reflects from the target carrying new frequencies (e.g., $2f_0$, $3f_0$, and so on). The radar receive (Rx) antenna captures the wave, which arrives back at the radar—with an e-field denoted by E_{rec}.

If the target were linear—as is the case with most nonelectronic targets and naturally occurring clutter objects—the set of frequencies received from the target (in E_{rec}) would match the set of frequencies transmitted to the target (in E_{trans}). All practical electronics are, however, nonlinear, because the voltage across an element and the current through that same element is never perfectly linearly proportional. When a powerful enough E_{inc} is incident on a component, the voltage across the component generates a current that deviates from the linear proportionality, and that current generates a reflected E_{refl}, which contains at least one frequency that was not part of E_{inc}.

Conductors that are not intended to carry electricity, such as rusted metals and junctions between metals,[5,6] are nonlinear, but they require high incident power (e.g., W/m^2) to generate new frequencies. Elements that pass electricity but do not significantly alter it or store significant amounts of it, such as connectors and attenuators,[7,8] are also weakly nonlinear. Semiconductor-based elements, that is, those commonly found in electronic devices—such as amplifiers,[9] mixers,[10] and frequency doublers[11,12]—are strongly nonlinear and thus they require only a moderate amount of incident RF power (e.g., mW/m^2) to generate new frequencies. Even lower power (e.g., $\mu W/m^2$) is required when those electronics are connected to an antenna, as is typically the case in communications devices.

The radar operator is aware of which frequencies were transmitted into the environment. If an electronic device is present within that environment, antennas of opportunity on its circuit board capture some of the energy of this wave. Some of this captured energy is modulated by the semiconductor junctions of the electronics connected to these antennas; this modulation generates frequencies that were not part of the original transmission. Some of the new frequencies are reemitted wirelessly from the device by these same antennas. If new frequencies (i.e., not part of the original probe set) are received by the radar, the presence of an electronic device is detected.

In this manner, it is possible to design a radar transmission to force electronic devices to radiate new signals that give away the locations of (and possibly unique signatures associated with) those electronics. NLR is used instead of traditional (linear) radar because traditional radars have difficulty separating handheld targets (with small radar cross sections) from nearby clutter. Because only manmade electronics (with few exceptions, such as naturally occurring ferromagnetic materials) reemit waves at different frequencies; such nonlinear targets are more easily discernible from naturally occurring clutter.

One of the longest-running applications for NLR research is the tracking of invasive insects.[13,14] Much effort has been devoted to fabricating lightweight antennas that are conformal to the bodies of those insects.[15,16] Other applications focus on providing information about humans and their anatomy: tracking people's movements,[17,18] locating a submerged lifejacket,[19] alerting a vehicle driver to the presence of vulnerable road users,[20,21] distinguishing between benign and harmful intent,[22] monitoring vital signs,[23,24] and pinpointing the depth of a feeding tube.[25]

Radars that address metal junctions have been used to locate breaks in metallic structures caused by fatigue,[26] cracks in walls,[27] and underground assets such as pipelines.[28,29] Those radars tailored to semiconductors have been used to conduct countersurveillance,[30] to detect weapons at security checkpoints,[31] and to reveal the presence of other radar systems.[32] The NLRs that most closely resemble the authors' work have been used to find RF front-end electronics,[33–36] such as those circuits found in cell phones,[37,38] handheld radios,[11,39] and smart devices.[40] Short-range radars have often been used to detect electronics[41] or explosives[42] in parcels at security checkpoints.

3. NLR Theory and Waveforms

A useful model for the behavior of an electromagnetically nonlinear target under illumination by a wave is the memoryless power series[6,8,9,20,36,39,42–46]

$$E_{\text{refl}}\left(t\right) = \sum_{m=1}^{M} a_m E_{\text{inc}}^{m}\left(t\right) \tag{1}$$

where E_{inc} and E_{refl} are the aforementioned incident and reflected electric fields (observed at the target) and a_m are complex power-series coefficients corresponding to the amplitude and phase responses of the target at each harmonic of the original wave E_{inc}. The coefficient a_1 is the linear response of the target. The coefficients a_m for $m > 1$ depend upon the nonlinear properties of the target.

While a Volterra series model[47] would be a more complete way to model a nonlinear element (since that model accounts for memory effects), the power-series expression that neglects memory effects has, to date, been adequate to model nonlinear targets of interest. The entire channel between the transmitter and receiver, including the nonlinear target, has been described mathematically in several references. Many of those descriptions derive some version of the NLR range equation, which is a variant of the Friis equation for a monostatic radar, extended to a nonlinear receive mode.[7,11,12,17,27,28,34,38,48,49]

NLRs can be classified broadly according to the waveforms that they transit and receive. If a single RF tone is transmitted,

$$E_{\text{trans}}(t) = E_0 \cos(2\pi f_0 \cdot t) \tag{2}$$

then, by the model assumed in Equation 1, the reflection from the target will be

$$E_{\text{refl}}(t) = \sum_{M=1}^{\infty} |E_M| \cos(2\pi \cdot M f_0 \cdot t + \phi\{E_M\}) \tag{3}$$

where E_0 is the amplitude of the transmitted electric field, and $|E_M|$ and $\phi\{E_M\}$ are the amplitude and phase of each harmonic reflected from the target.

To date, the most common arrangement is to transmit a single RF tone and receive twice that frequency (M = 2, called the "2nd harmonic")[15,27,29,50–57] as depicted in Figure 2a. Another popular arrangement is to transmit a single RF tone and to receive triple that frequency (M = 3, the "3rd harmonic")[5,58–62] as depicted in Figure 2b.

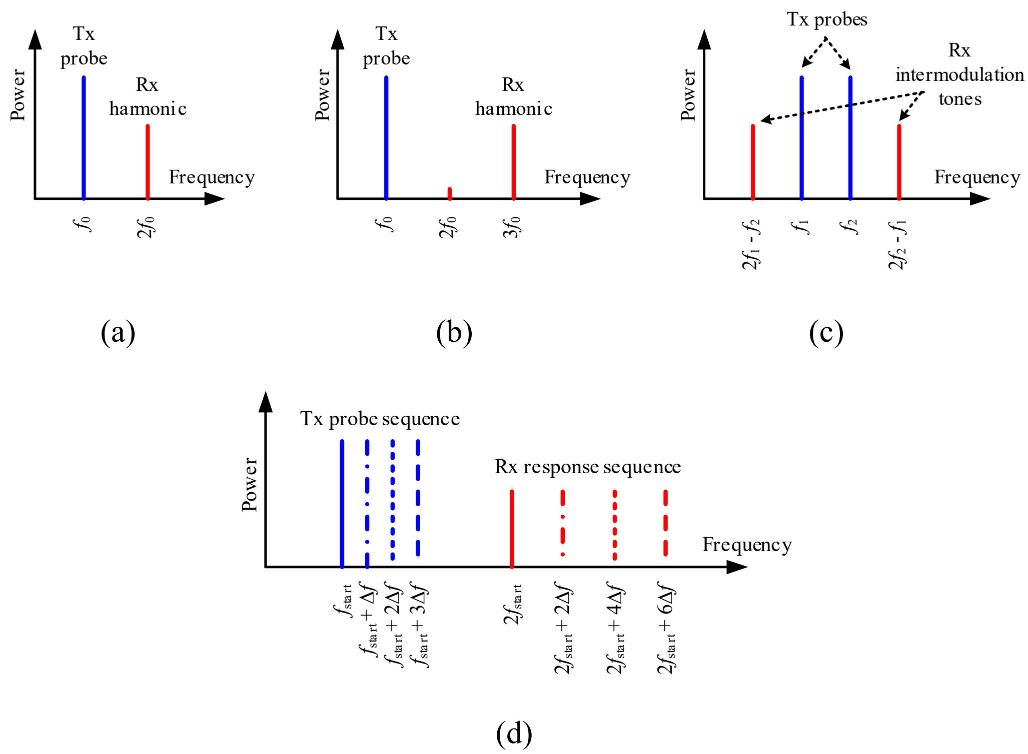

Figure 2. Four schemes for transmit/receive waveforms: (a) Tx single probe frequency, Rx single 2nd-harmonic response, (b) Tx single probe frequency, Rx single 3rd-harmonic response, (c) Tx two simultaneous frequencies, Rx intermodulation, (d) Tx single frequencies in sequence, Rx harmonics in sequence. In case (d), the bandwidth of the received sequence (6Δf) is double the bandwidth of the transmitted sequence (3Δf) for M = 2.

For the transmit and receive frequencies to occupy the same frequency band, two tones (typically spaced 1 MHz apart or less) can be sent,

$$E_{trans}(t) = E_0 \cos(2\pi f_1 \cdot t) + E_0 \cos(2\pi f_2 \cdot t) \quad (4)$$

and a group of new frequencies is generated close to the original transmitted frequencies, such as $2f_1 - f_2$ and $2f_2 - f_1$, called "intermodulation."[9,23,24,33,37,63–65] This Tx/Rx arrangement is depicted in Figure 2c. An advantage of receiving intermodulation is that a single antenna may be used for Tx and Rx. A disadvantage of receiving intermodulation is that removing the original Tx frequencies from the Rx waveform (to maximize system sensitivity, e.g., to achieve appropriate standoff distance between the radar and the target) requires increased complexity compared to harmonic architectures. For example, some intermodulation-radar architectures implement feedforward cancellation (rather than passive filtering) to eliminate f_1 and f_2 from the Tx waveform.

A clever twist on the aforementioned arrangement is to transmit a single RF tone and to receive the intermodulation resulting from the mixing of the radar's f_1 with an f_2 generated by the target itself (e.g., its clock or its own carrier frequency).[66] Additional spectral content, useful for coarse ranging or for rudimentary classification of targets, may be generated by sweeping the radar's closely spaced transmit frequencies over a narrow band and receiving the corresponding swept intermodulation tones.[6,32,67] More precise ranging may be accomplished by sweeping the simultaneous f_1 and f_2 over a wider band.[34,36] Removing f_1 and f_2 from the Rx waveform is made easier (e.g., by passive filtering) if the radar receives intermodulation tones centered around a harmonic of the Tx frequencies, such as $3f_1 - f_2$ and $3f_2 - f_1$, which are centered around $2f_1$ and $2f_2$.[20,30,68] Depending on the particular f_1 and f_2 used, especially if those frequencies are in the 10s of gigahertz (i.e., relatively high for radar), the radar might instead receive difference tones closer to 0 Hz, such as $f_2 - f_1$ and $2f_2 - 2f_1$.[8,69]

Early versions of NLRs were called "nonlinear junction detectors" (NLJDs). These systems were unable to establish range to target, largely because they collected narrowband responses, most often only a single harmonic ($2f_0$ or $3f_0$). Later systems determined range to target by transmitting and receiving a wider spectrum, such as by sending a baseband pulse and observing time-domain[70] or frequency-domain[42] distortion, transmitting a frequency sweep and capturing time-domain distortion,[41] or by modulating f_0 with a Gaussian pulse[71] or a phase-shift-keying sequence[16,58,72] and receiving similar modulation near $2f_0$. Classification, a precursor to identification, was enabled by radars that captured multiple harmonics.[43]

As of publication of this report, the latest and arguably most popular instantiation of NLR transmits a single-tone f_0, which steps or sweeps continuously through a band of frequencies.[11,12,18,22,39,44,46,47,73–76] The radar captures the stepped/swept harmonic $2f_0$ in complex-amplitude form (which includes phase information). Processing of the full complex-valued sequence of harmonics produces high-resolution range profiles; ultra-wideband (UWB) systems can generate high-resolution images of targets containing minimal (linear) clutter.

For a stepped-frequency radar, the transmit tone increases from a start frequency f_{start} to an end frequency f_{end} with an even spacing Δf:

$$E_{\text{trans}}(t) = E_0 \cos\left[2\pi \cdot f(t) \cdot t\right]$$

$$f(t) = \begin{cases} f_{\text{start}} , & 0 \le t < \Delta t \\ f_{\text{start}} + \Delta f , & \Delta t \le t < 2\Delta t \\ f_{\text{start}} + 2\Delta f , & 2\Delta t \le t < 3\Delta t \\ \cdots & \cdots \\ f_{\text{end}} - \Delta f , & T - \Delta t \le t < T \end{cases} \tag{5}$$

where N_{step} is the number of discrete frequency steps between f_{start} and f_{end} , T is the full length of the stepped-frequency pulse, and $\Delta t = T/N_{\text{step}}$ is the spacing in time between each step. The received waveform is also stepped in time; it contains a sequence of harmonics

$$E_{\text{rec}}(t) = \left|E'_M\right| \cos\left[2\pi \cdot M \cdot f(t) \cdot (t - 2\tau) + \phi\{E'_M\}\right] \tag{6}$$

where 2τ is the time of flight from the radar transmitter to the target, and back to the receiver. The prime notation denotes that the amplitudes and phases of each harmonic are described at the radar receiver (instead of at the target). This Tx/Rx arrangement is depicted in Figure 2d for $N_{\text{step}} = 4$.

4. Frequency of Operation and Antennas

The choice of operating frequencies for a radar system is influenced by different factors. One factor is target size; generally, for an electromagnetic (EM) wave to scatter enough energy for a radar to “see” the target, the Tx wavelength must be comparable to or smaller than the size of the target. In other words, the Tx frequency must be above a certain threshold to resolve multiple targets, or to separate targets from clutter objects. Another factor is penetration depth; generally, lower frequencies propagate more efficiently through material media. Skin depth narrows with increasing frequency; at higher frequencies, materials between the radar and the target are more absorptive of EM waves. In other words, receiving high-frequency waves requires transmitting high power, especially when targets are buried or otherwise obscured. Thus, when choosing Tx and Rx frequencies, a radar engineer must negotiate a tradeoff between range to target (detection at a distance) and resolution (probability of detection and certainty of classification).

Different systems have negotiated this tradeoff in different ways. Table 1 lists the frequencies of systems that have openly reported that specification. The continuous-wave or narrowband (NLJD) systems generally transmit only f_0, a narrowly modulated spectrum centered on f_0, or closely spaced tones (f_1 and f_2). A handful of systems transmit widely separated tones f_1 and f_2. The modern (imaging) systems operate over a wide band, between ultra-high frequencies (UHFs, down to 300 MHz) and W-band (up to about 87 GHz).

Table 1. Operating frequencies of NLRs reported in open literature.

Systems	Tx frequencies	References
Continuous-wave or narrowband	400, 434 MHz	37, 77
	752, 865 MHz	32, 28
	900, 915 MHz	9, 33, 61
	1.0, 1.2 GHz	20, 51, 50
	2.45, 2.5, 2.55 GHz	27, 55, 17, 29
	2.9, 3, 3.1, 3.5, 4 GHz	14, 78, 38, 26, 79, 80
	5.3, 5.5, 5.8 GHz	81, 82, 23–25, 45
	9.4, 10, 12, 14, 20 GHz	13, 83, 57, 84, 76, 85
Widely separated tones	800 MHz and 900 MHz	30
	935 MHz and 960 MHz	8
	77 GHz and 87 GHz	69
Wideband and UWB	350 MHz to 700 MHz	39
	300 MHz to 2.5 GHz	34
	300 MHz to 3 GHz	73
	300 MHz to 6 GHz	36
	400 MHz to 3.5 GHz	86
	800 MHz to 1 GHz	11
	1950 MHz to 2050 MHz	6
	2.0 GHz to 2.6 GHz	75
	2 GHz to 3 GHz	47, 56, 74
	2.4 GHz to 2.5 GHz	46
	2.7 GHz to 3.1 GHz	71
	2.90 GHz to 2.94 GHz	48
	2.9 GHz to 3.3 GHz	87
	24 GHz to 24.5 GHz	41
	60 GHz to 64 GHz	12
	56 GHz to 63 GHz	18
	76 GHz to 81 GHz	21

Antennas are generally sized according to wavelength; that is, they correspond to the frequencies chosen for Tx and Rx. The shape of the antenna is usually selected according to the gain and degree of directionality desired. For example, horn antennas are high gain with a narrow beamwidth while patches are low gain with a wide beamwidth. The advantage of high gain is the ability to place higher power on target to activate the nonlinearity and increase probability of detection in the line of sight of the antenna; the disadvantage is that a radar with one such antenna will often miss targets that are just outside the line of sight. Some systems employ multiple antennas or synthetic apertures to widen the radar's field of view.

Table 2 lists the antennas employed by different radar systems. A handful of systems use a single antenna[23,37] because the same frequency band is used for Tx and Rx; a circulator or a diplexer[52] can decouple the Tx and Rx chains. Some systems employ a single antenna capable of operating in two widely separated frequency bands.[48,54,73,84] Most systems use two antennas of the same type (size, shape) for Tx and Rx.

Table 2. Antennas implemented in NLR systems.

Antenna type	References
Array (repeated elements)	11, 71, 84, 88
Helical: UWB	86
Horn: ridged	51, 75
Horns: standard gain	26, 38, 57, 76
Log-periodic array (LPA)	11, 37, 56
Patches—microstrip	12, 78, 80, 85
Patch, circular (Tx)/spiral, circular (Rx)	6
Waveguide: slotted	16
Vivaldi	29, 71
Yagi-Uda: planar	27

5. High Power with High Linearity

Arguably the primary advantage of NLR versus traditional radar is clutter suppression. Most naturally occurring and manmade clutter items are linear, and thus the received wave contains no new frequencies as compared to the transmitted wave. Generating new frequencies from nonlinear targets comes at a price, however, as the power required to generate (harmonic, and intermodulation) frequencies is typically much higher than that of a comparable linear radar. It is challenging to produce such high power from a transmitter without also generating distortion (harmonics, and intermodulation) in the Tx waveform. Such distortion can couple from the Tx antenna to the Rx antenna directly, or it can be sent from the Tx antenna to a clutter object, which reflects linearly back to the radar; in either case, that distortion can generate false alarms.

Several solutions have been developed to keep the waveform sent to the Tx antenna distortionless. The most common solution is passive low-pass filtering; that is, absorbing minimal power while achieving high insertion loss at harmonics of the transmit frequency f_0.[12,16,39,54,71,73,77,88,89] Some architectures employ band-pass filters rather than low-pass filters.[46,61]

The waveform reflected from a nonlinear target will almost always contain more power at the Tx frequencies than at the new (harmonic and intermodulation) frequencies. If those Tx frequencies are not suppressed in the receiver before data capture, the small nonlinear target response can be masked by the much-larger linear target response. Furthermore, if the Rx waveform is amplified before data capture, the linear response could saturate the receiver's detector. In other words, the presence of the original Tx frequencies in the target response can generate distortion in the receiver, even if the Rx waveform is time-gated to eliminate direct coupling from the Tx antenna to the Rx antenna.

The same architectures that implement low-pass filtering in the transmitter to suppress harmonics ($2f_0$, $3f_0$) before the Tx antenna typically implement high-pass filtering to suppress the fundamental frequency (f_0) immediately after the Rx antenna (before the Rx data stream is amplified and captured). For radars whose Tx and Rx frequencies occupy the same band (e.g., for intermodulation radars), isolators can be used to separate the Tx and Rx waveforms.[24,34,37] Unfortunately, those isolators are typically magnetic and often generate their own distortion; thus, such systems sometimes require feedforward cancellation to adequately suppress the Tx frequencies (f_1 and f_2) in the target response.[90]

To prevent the buildup of standing waves inside the transmitter (and subsequent radiation of system-generated distortion from circuit-board traces and cables, independent of the Tx antenna), diplexers may be substituted for reflective filters.[7,9,10,19,91] In a back-to-back dual-diplexer arrangement, the low-pass Tx line may be routed from the transmitter to the Tx antenna while the high-pass Tx line may be routed from the transmitter directly to a matched load to absorb Tx harmonics; also, the high-pass Rx line may be routed from the Rx antenna to the rest of the receiver while the low-pass Rx line may be routed from the Rx antenna directly to a matched load to absorb the linear target response.

Other clever solutions for mitigating system-generated distortion are as follows:

- combining low-pass/high-pass filtering with feedforward cancellation, routing reflected harmonics to cancel harmonics regenerated by the power amplifier just before the Tx antenna,[92]
- incorporating a filter (which attenuates a particularly strong harmonic) into the matching network at the output of the power amplifier,[93] and
- using a band-pass filter to combine multiple time-multiplexed tones from the amplifier into simultaneous multitones fed to the Tx antenna (for intermodulation radar).[63]

6. Target Imaging, Tracking, and Classification

As computer processors become faster and memory becomes deeper, more radars will be able to generate 2D (and even 3D) images of scenes. Over time, those images will reveal a greater number of targets, indicate more precise locations for those targets, and classify them with greater accuracy. Some systems transmit a wide band of frequencies, receive complex amplitudes, and form range profiles using the inverse Fourier transform.[11,88] Other systems transmit narrow pulses and use time reversal to focus their images.[71] A radar that captures a higher harmonic ($M \cdot f_0$) can achieve narrower range resolution because resolution is inversely proportional to receive bandwidth and receive bandwidth is linearly proportional to M.[94] Achieving fine resolution in cross range is possible for narrow (high-gain) antennas if a synthetic aperture is employed across the scene.[26,75,95]

To track targets, researchers have investigated the following:

- an inverse-Fourier-transform-based algorithm,[11]
- Doppler frequency shift at harmonics,[24] and
- several different sensor nodes for multilateration.[96]

To recognize targets in situ (i.e., when a radar is ultimately deployed), libraries of device signatures can be collected (during radar development) and referenced later (during radar operation). Toward that end, different techniques are employed to distinguish between targets and classify them including the following:

- ranking targets according to Doppler shift imparted onto the Rx wave,[17,22,23]
- comparing strengths of responses received at different harmonics,[5,97]
- computing basic statistics (e.g., mean and variance) for lower harmonics,[98]
- computing advanced statistics (e.g., skewness and kurtosis) for higher harmonics,[35,43]
- sweeping transmit power and plotting distortion received versus Tx power,[32,33,39]
- sweeping transmit frequency and plotting distortion received versus Tx frequency,[40]
- forming wavelets unique to distorted time-domain responses,[41] and
- applying machine learning to differentiate between the scattering patterns generated by UWB tomography.[99]

The authors believe that AI, trained with the wide variety and large size of datasets collected by UWB systems, is likely to vastly improve radar–target recognition in the future.

7. Tags as Targets and Detection Range

For the authors' application, detecting and identifying RF electronics that are hidden or obscured, a typical target is preassembled and it is already designed to communicate (in a particular frequency band, using a particular modulation) with a secondary device. For many other applications, for example, the tracking of targets that are not electronic, specialized tags are designed to maximally respond to the incident (transmitted) radar wave and those tags are attached to the nonelectronic targets for tracking. Many tags employ a Schottky diode as the nonlinearity, since a single diode is a simple (cheap, small) component and because the Schottky variety responds very quickly (which is essential for generating distortion from gigahertz radar waves).

A list of tag architectures found in the literature is provided in Table 3. While such nonlinearities are not the intended targets of many radar systems, some of these tags could be used as calibration targets during the development of those same systems.

Table 3. Tags used as NLR targets.

Tag architecture	References
Schottky diode + dipole, wire	13, 14, 15, 25, 57, 100
Diode + dipole, bowtie	46, 55, 75
Diode + dipole, folded	19
Diode + dipole, meandered	77
Diode + slot, annular	50
Diode + slot, spiral	79
Diode + patch, round	80
Diode + patch, square	28, 29, 81
Diode + Rotman lens, dual band	76
Diode + tape, copper	27
Diode + transmission-line stubs	24, 52
2 diodes + dedicated matching circuits	51
Graphene-based electronics	101
Silicon-on-insulator field-effect transistors	83
RFID + microstrip, dual band	61

One metric by which radars are evaluated is maximum detection range. However, it would be unfair to use this one metric to compare two different systems, as other metrics (e.g., sensitivity, circuit complexity, power requirements, and processing requirements) might be equally important.

A couple of experiments have shown proof-of-concept nonlinear detection by direct injection of the radar Tx probe into front-end electronics and capture of the Rx waveform using a directional coupler.[9,33] A handful of experiments have used near-field scans (e.g., antennas in close proximity or transverse-EM cells

[TEM]).[6,39,102,103] Distances reported in open literature are reported in Figure 3. The largest standoff distances between the radar and the target (e.g., over 5 km) are achieved when the target is a nonlinear tag that has been tailored to react strongly to the radar's transmit waveform.[19]

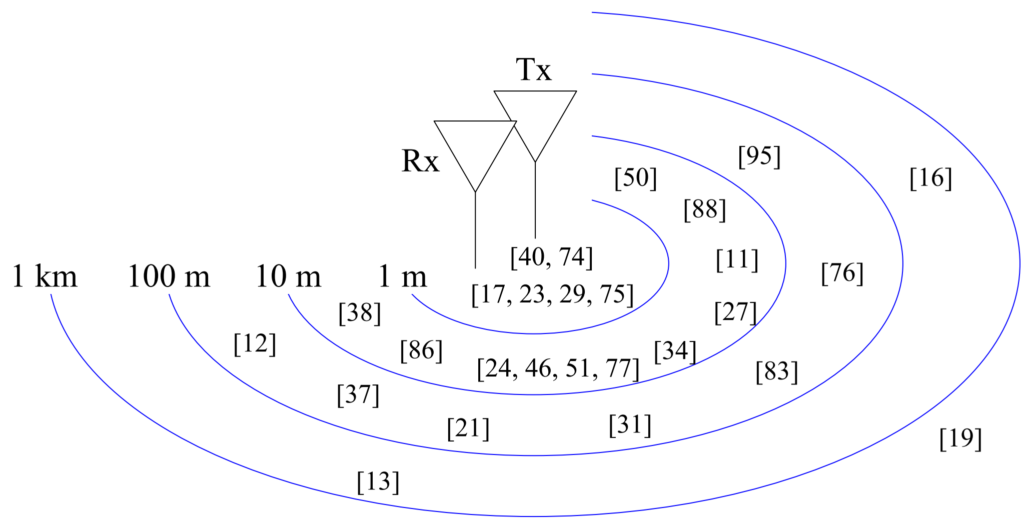

Figure 3. Demonstrated standoff distances (between the radar and the target). The bistatic radar is at the center; the location of the bracketed reference on the chart denotes the reported distance to target. References are grouped logarithmically, e.g., the distances reported by the two references just inside the outer ring were between 100 m and 1 km.

8. Additional Novel NLR Research

While reading articles relevant to NLR written over the past 8 years, the authors became aware of many interesting research threads, each of which is probably novel enough to warrant its own literature review. These novel ideas are summarized in the bulleted list below, with the intention of drawing the attention of NLR researchers to them (for possible incorporation of these ideas into their own NLR work).

- For quicker initial prototyping of a future radar system, a software-defined radio can be used as the radar's transceiver (as an alternative to using RF instruments or more powerful radar-specific integrated circuits).[104]
- On the benchtop (i.e., without needing an anechoic chamber), nonlinear detection and classification may be simulated using a TEM cell.[39]
- Linear and nonlinear radar systems may be merged onto the same platform for improved detection.[88,105] At least one system merged NLJD with an inductive metal-detector-type sensor to reduce false alarms.[6]
- Multiple forms of NLR (e.g., harmonic and intermodulation systems) may be merged onto the same platform for improved detection.[44]

- Signal-processing algorithms used for through-the-wall sensing in traditional/linear radar may be incorporated into harmonic/intermodulation radar to sense nonlinear targets through the wall.[106]
- As with traditional/linear radar, defocusing of target images is caused by multipath.[47] In particular, intermodulation may result from receiving the same reflected harmonic from two or more different paths between the target and the radar (i.e., at slightly different points along the modulation of the Tx waveform).[82]
- A support-vector-machine-based algorithm may be implemented to remove noise from harmonics, which is particularly useful for NLR since target responses are typically very weak (i.e., usually under the noise floor).[5]
- The strength of a nonlinear response can depend strongly on the physical orientation of the target (e.g., the polarization of the target's antenna vs. the radar's antenna).[107]
- Stronger nonlinear responses may be generated from targets by transmitting probes from multiple nodes (e.g., from multiple drones carrying RF transmitters, with a single RF receiver at a base-station capturing all responses).[53]
- Stronger intermodulation responses may be generated by allocating unequal power between multiple transmit tones.[45]
- Stronger responses may be generated from nonlinear tags by combining impedance-matching and fundamental-tone-suppression (filtering); the combination achieves high conversion gain (e.g., from f_0 to $2f_0$) while minimizing linear reflections (e.g., at f_0).[64] Also, independent matching networks at Tx and Rx frequencies (e.g., f_0 vs. $2f_0$) can be used to suppress linear reflections while enhancing harmonic reflections.[100]
- Frequency-selective metallic structures may be placed as dividers between Tx and Rx antennas (e.g., atop a radar platform) to suppress harmonic coupling between the transmitter and the receiver[108]; reducing such coupling generally increases receiver sensitivity and increases the distance at which a nonlinear target may be detected.

9. Conclusion

This report summarized over 100 articles relevant to NLR. The period 2017–2024 saw an expansion of applications for NLR technology. The mathematics that model nonlinear (field–circuit) interactions has largely remained unchanged from prior decades. To date, the most popular nonlinear interaction to exploit for target detection is the 2nd harmonic ($2f_0$), followed by intermodulation ($2f_1 - f_2$, $2f_2 - f_1$)

and the 3rd harmonic ($3f_0$). High-resolution imaging of targets and clutter was enabled by UWB systems, transmitting a stepped or swept f_0 and processing complex-amplitude data captured at $2f_0$.

Many different frequency bands have been used; all NLR systems transmit RF power somewhere between UHF and W-band. No single radar-antenna geometry is widespread, although horns and patches and LPAs are common. High linearity is accomplished most often by passive filtering; diplexers demonstrate improved linearity compared to reflective architectures. Currently, classification of nonlinear targets is still in its infancy; no single technique is yet dominant.

To date, the overwhelming majority of nonlinear tags include a Schottky diode; different tag-antennas have helped maximize reflected-signal strength. Detection of nonlinear tags has been demonstrated to nearly 6 km; it remains to be seen whether a comparable detection distance is possible for targets that have not been tailored to the radar (e.g., for RF electronics that were not designed to be found by an NLR).

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List of Symbols, Abbreviations, and Acronyms

2D/3D	two-/three-dimensional
AI	artificial intelligence
ALC	Adelphi Laboratory Center
ARL	Army Research Laboratory
DEVCOM	U.S. Army Combat Capabilities Development Command
EM	electromagnetic
GTS	General Technical Services, LLC
LPA	log-periodic array
NLJD	nonlinear junction detector
NLR	nonlinear radar
RF	radio frequency
RFID	RF identification
Rx	radar receive
TEM	transverse electromagnetic
Tx	radar transmit
UHF	ultra-high frequency
UWB	ultra-wideband

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