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Waveform Optimization for Enhanced Target Coordinate Estimation in Multistatic Radar Systems

Abstract: The relevance of this study is determined by the rapid development of modern air attack means, including unmanned aerial vehicles, cruise missiles and other small aerial objects, which significantly increases the requirements for airspace surveillance and target localisation systems. The research problem lies in the fact that the accuracy of target coordinate estimation in multistatic radar systems depends not only on the spatial configuration of transmitting and receiving positions, but also on the structure, bandwidth and correlation properties of the probing waveform. The scientific novelty of the study consists in a comparative simulation-based assessment of conventional pulse, linear frequency modulated and phase-coded probing signals under identical multistatic radar conditions, with a focus on their influence on ranging accuracy and coordinate estimation error. The object of the study is the process of target coordinate estimation in multistatic radar systems using the ranging method. The aim of the research is to evaluate how probing waveform characteristics affect target localisation accuracy and to determine which waveform types provide the most effective reduction of coordinate estimation errors. The methodology is based on mathematical and simulation modelling of a three-position multistatic radar system in MATLAB, Monte Carlo experiments, correlation-based signal delay estimation, range measurement modelling and statistical analysis of target coordinate estimation errors. The investigated waveforms include conventional rectangular pulses, linear frequency modulated signals with different frequency deviations, and phase-coded modulation signals, including Barker-coded and long Frank-coded waveforms. The results show that conventional pulse signals provide the lowest localisation accuracy because of their limited bandwidth and insufficient range resolution. Linear frequency modulated signals significantly improve coordinate estimation accuracy due to pulse compression and increased effective bandwidth, while long phase-coded waveforms also demonstrate high performance owing to favourable autocorrelation properties and a large time-bandwidth product. The study confirms that waveform optimisation is one of the most effective ways to improve ranging-based localisation in multistatic radar systems without changing the radar network geometry. The obtained findings may be used in the design and modernisation of radar systems intended for the detection, tracking and localisation of small aerial targets under complex airspace surveillance conditions.

Keywords: multistatic radar system, target localization, coordinate estimation accuracy, probing signal, ranging method, unmanned aerial vehicle, airspace surveillance.

Abbreviations:

LFM is linear frequency modulated,

OFDM is orthogonal frequency-division multiplexing,

PCM is phase-coded modulation,

UAV is unmanned aerial vehicle.

Introduction

In recent years, the rapid development of air attack means, particularly UAVs, cruise missiles and other small aerial objects, has created new challenges for radar surveillance systems. The reliable detection of such targets and the accurate determination of their spatial coordinates are essential for ensuring effective airspace monitoring and supporting decision-making processes in air defence systems. The increasing complexity of the air environment, combined with the widespread use of low-observable, small-sized and manoeuvring aerial targets, requires continuous improvement of radar technologies, target localisation algorithms and signal processing methods.

The relevance of this study is determined by the growing need to improve the accuracy of target coordinate estimation under conditions of complex airspace surveillance. Modern air defence and air traffic monitoring systems must operate in an environment characterised by high target manoeuvrability, reduced radar cross-section, electronic countermeasures and limited reaction time. Under such conditions, even moderate coordinate estimation errors may reduce the effectiveness of tracking, classification, engagement asset allocation and interception. Therefore, improving the accuracy and reliability of target localisation is a critical scientific and engineering task for contemporary radar systems.

One of the key factors affecting the effectiveness of target interception and tracking is the accuracy of coordinate information. High-precision target localisation enables more efficient use of available engagement assets and improves the overall performance of air defence systems. In this context, multistatic radar systems represent a promising technological direction. Due to the spatial distribution of transmitting and receiving modules, multistatic radar systems provide additional target observation opportunities, improved resistance to jamming, enhanced system survivability and better geometric diversity compared with conventional monostatic radar systems (*Cherniak, 1998; Griffiths et al., 2019; Willis, 2005*).

The research problem lies in the fact that, although multistatic radar systems can improve target observability due to distributed geometry, the accuracy of coordinate estimation remains strongly dependent on the quality of range measurements. In ranging-based localisation, target coordinates are determined from measured signal propagation delays. Therefore, any error in delay estimation is transformed into range error and subsequently into coordinate estimation error. The magnitude of this error depends not only on radar position geometry and measurement noise, but also on the structure and characteristics of the probing waveform, including pulse duration, bandwidth, modulation type, correlation properties and time-bandwidth product (*Levanon & Mozeson, 2004; Richards, 2014; Skolnik, 2008*).

Traditional pulse signals are relatively simple to implement but have limited range resolution because their resolution is directly related to pulse duration and effective bandwidth. Shorter pulses may improve range resolution, but they also reduce transmitted energy, which may adversely affect detection performance. Modern radar systems therefore increasingly employ wideband and coded waveforms, including linear frequency modulated signals and phase-coded signals, which provide improved range resolution, processing gain and more favourable correlation characteristics. However, the comparative influence of different waveform types on ranging-based coordinate estimation accuracy in multistatic radar systems requires additional quantitative analysis.

The hypothesis of the study is that optimisation of probing waveform parameters can significantly improve target coordinate estimation accuracy in multistatic radar systems without changing the spatial configuration of radar positions. It is assumed that signals with larger effective bandwidth, higher time-bandwidth product and more favourable autocorrelation properties provide more accurate delay and range measurements, which in turn reduce the spatial dispersion of estimated target coordinates. Accordingly, wideband linear frequency modulated waveforms and long phase-coded waveforms are expected to outperform conventional rectangular pulse signals in multistatic localisation tasks.

The scientific novelty of the study consists in a comparative simulation-based evaluation of the influence of probing waveform characteristics on target coordinate estimation accuracy in a multistatic radar system using the ranging method. Unlike approaches that analyse radar waveforms primarily from the standpoint of detection or range resolution alone, the present study focuses on the full localisation chain: waveform structure, delay estimation, range measurement error and resulting coordinate estimation accuracy. The study compares conventional rectangular pulses, linear frequency modulated waveforms and phase-coded modulation signals under identical simulation conditions, thereby allowing their localisation performance to be assessed within the same multistatic geometry.

The object of the study is the process of target coordinate estimation in multistatic radar systems using the ranging method.

The subject of the study is the influence of probing waveform parameters, including bandwidth, modulation type and correlation properties, on range measurement accuracy and target localisation error in a distributed radar configuration.

The study aims to evaluate the influence of different probing waveforms on target coordinate estimation accuracy in a multistatic radar system and to determine which waveform types provide the most effective reduction of localisation errors when the ranging method is used.

To achieve this aim, the following research tasks are set:

- to analyse the role of multistatic radar systems in improving airspace surveillance and target localisation accuracy;
- to identify the main factors affecting coordinate estimation accuracy when the ranging method is applied;
- to examine the influence of probing waveform structure on delay and range measurement accuracy;
- to develop a simulation model of a three-position multistatic radar system operating within a common information-processing framework;

- to compare conventional rectangular pulses, linear frequency modulated signals and phase-coded modulation signals under identical modelling conditions;
- to evaluate the spatial distribution of target coordinate estimates obtained through Monte Carlo simulation experiments;
- to determine the relationship between signal bandwidth, time-bandwidth product, correlation properties and localisation accuracy;
- to identify waveform types that provide the most favourable balance between coordinate estimation accuracy, implementation feasibility and operational applicability.

The methodological basis of the study includes mathematical modelling, simulation modelling, correlation-based signal delay estimation, Monte Carlo experiments and statistical analysis of coordinate estimation errors. A three-position multistatic radar system is considered, in which several spatially separated radar positions jointly perform target localisation using independent range measurements. The simulation model reproduces range estimation errors and uncertainties associated with signal processing. The comparative assessment is carried out for conventional pulse signals, linear frequency modulated signals with different frequency deviations and phase-coded waveforms, including Barker-coded and long Frank-coded signals.

The theoretical significance of the study lies in clarifying the relationship between probing waveform characteristics and coordinate estimation accuracy in multistatic radar systems. The research contributes to radar signal processing theory by showing how waveform bandwidth, modulation structure and autocorrelation properties influence not only range resolution, but also the final spatial localisation accuracy of a distributed radar system. The study also develops the theoretical understanding of the multiplicative effect of range measurement improvement in multistatic configurations, where reductions in individual ranging errors can lead to a substantial decrease in overall coordinate uncertainty.

The practical significance of the results lies in the possibility of using the obtained findings for the design, modernisation and optimisation of multistatic radar systems intended for airspace surveillance, detection and tracking of small aerial objects. The results may support the selection of probing waveforms for radar systems operating against UAVs, cruise missiles and other low-observable aerial targets. In practical terms, the study indicates that wideband linear frequency modulated waveforms may provide the most advantageous balance between localisation accuracy, energy efficiency and technological maturity, while long phase-coded waveforms may be useful where improved correlation properties and interference resistance are required.

Thus, the present study addresses an important problem of modern radar engineering: how to improve target coordinate estimation accuracy in multistatic radar systems through rational waveform selection and optimisation. The results are expected to contribute to the development of more accurate, reliable and operationally effective radar systems for complex airspace surveillance and air defence applications.

Methods

The research was conducted using mathematical and simulation modeling methods to evaluate the influence of probing signal parameters on the accuracy of target coordinate estimation in a multistatic radar system. The considered consisted of several spatially separated radar positions

operating within a common information-processing framework and jointly performing target localization using the ranging method.

The coordinate estimation process was based on independent range measurements obtained from multiple radar positions. The target location was determined by combining distance measurements from different observation points and calculating the most probable target coordinates. This approach allows the influence of measurement errors to be reduced and improves localization accuracy compared with conventional single-position radar systems.

To investigate the influence of probing signal characteristics, a simulation model was developed in MATLAB. The model reproduced the operation of a multistatic radar system under realistic measurement conditions, including range estimation errors and uncertainties associated with signal processing. The simulation environment enabled repeated experiments under identical conditions while varying only the parameters of the transmitted signal.

The studied radar configuration included three radar positions arranged in a distributed geometry with overlapping coverage areas. A target was placed within the common surveillance region, and range measurements from all radar positions were used to estimate its coordinates. The localization process was repeated multiple times to obtain statistically reliable results and to evaluate the distribution of coordinate estimation errors.

Several signal types commonly used in radar systems were considered. These included conventional rectangular pulses, LFM signals, and PCM signals with different bandwidths and coding structures. The selected signals represent different approaches to improving radar performance through increased bandwidth and signal time-bandwidth product.

For each signal type, a series of Monte Carlo simulation experiments was performed. The received signal delay was estimated using correlation-based processing techniques, and the corresponding range measurements were used for coordinate estimation. The accuracy of target localization was evaluated by analyzing the spatial distribution of estimated target positions and the corresponding coordinate errors.

The comparative assessment focused on the relationship between signal characteristics and localization performance. Particular attention was paid to the influence of signal bandwidth, modulation type, and correlation properties on range measurement accuracy and, consequently, on the overall coordinate estimation accuracy of the multistatic radar system.

Literature Review

Multistatic radar systems have attracted considerable attention in recent years due to their potential to improve target detection, tracking, and localization performance. The spatial separation of radar positions provides additional geometric diversity, increases system survivability, and enhances resistance to electronic countermeasures compared with conventional monostatic radar systems.

A significant number of studies have focused on target localization methods in multistatic radar networks. Among the available approaches, ranging-based methods remain one of the most widely used because of their relatively simple implementation and suitability for distributed radar architectures. In such systems, localization accuracy is primarily determined by the precision of range measurements and the geometric configuration of radar positions.

Previous research has shown that the characteristics of the probing signal strongly influence range estimation accuracy. Conventional unmodulated pulse signals are characterized by simple implementation; however, their range resolution is limited by pulse duration and available bandwidth. As a result, the achievable coordinate estimation accuracy may be insufficient for the detection and tracking of small aerial targets.

To overcome these limitations, modern radar systems increasingly employ wideband waveforms with intrapulse modulation. LFM signals have become one of the most common solutions due to their ability to provide pulse compression, improved range resolution, and high energy efficiency. Several studies report that increasing signal bandwidth significantly improves range measurement accuracy while maintaining sufficient detection performance.

PCM signals have also been extensively investigated in radar applications. Their advantages include improved correlation properties and enhanced resistance to interference. The localization performance of PCM signals depends on code length and waveform design, with longer codes generally providing better range estimation accuracy.

Recent studies have additionally considered advanced waveform designs, including OFDM and other wideband radar signals. Although these approaches offer promising localization capabilities, their practical implementation often requires increased computational complexity and strict synchronization requirements.

Despite extensive research on radar waveforms and multistatic radar architectures, limited attention has been paid to the combined influence of probing signal characteristics and ranging-based coordinate estimation accuracy in multistatic radar systems. In particular, the quantitative relationship between waveform parameters, range measurement accuracy, and resulting target localization performance requires further investigation.

Therefore, this study focuses on evaluating the impact of different probing signal types on coordinate estimation accuracy in a multistatic radar system employing the ranging method. Special attention is devoted to comparing conventional pulse signals, linear frequency modulated signals, and phase-coded waveforms under identical simulation conditions.

Results

The simulation study was conducted to evaluate the influence of probing waveform characteristics on target coordinate estimation accuracy in a multistatic radar system employing the ranging method. The investigated waveforms included conventional pulse signals, LFM signals, and PCM signals. For each waveform type, multiple Monte Carlo simulation runs were performed, and the resulting coordinate estimates were analyzed statistically.

The results obtained for conventional pulse signals confirmed the expected relationship between pulse duration and range resolution. A pulse duration of 2 μs produced a relatively large uncertainty region due to limited signal bandwidth. The estimated target positions exhibited considerable spatial dispersion, indicating insufficient ranging accuracy for high-precision localization tasks. Reducing the pulse duration to 1 μs improved the range resolution and reduced the spread of estimated target coordinates. However, the achieved accuracy remained limited compared with modern wideband waveforms.

The use of LFM signals resulted in a significant improvement in localization performance. For an LFM waveform with a frequency deviation of 400 kHz, the estimated coordinate distribution

became substantially more concentrated than in the case of conventional pulse signals. The reduction of coordinate dispersion demonstrated the positive effect of increased signal bandwidth on ranging accuracy. Further improvement was achieved when the frequency deviation was increased to 50 MHz. Under these conditions, the uncertainty region surrounding the true target position decreased considerably, and the majority of coordinate estimates were clustered close to the actual target location.

PCM waveforms also demonstrated improved ranging performance compared with conventional pulse signals. The Barker-coded waveform provided a noticeable reduction in coordinate estimation errors due to its favorable autocorrelation properties. The improvement became even more pronounced when a long phase-coded waveform based on a 169-element Frank code was employed. The resulting coordinate estimates formed a compact cluster around the true target position, indicating high localization accuracy and stable operation of the ranging algorithm.

The simulation results confirmed that increasing signal bandwidth and time-bandwidth product leads to improved delay estimation accuracy and, consequently, more accurate coordinate determination (*Figure 1*). Figure-based analysis showed a progressive reduction in the coordinate uncertainty region when moving from conventional pulse signals to LFM and long PCM waveforms.

A comparison of the investigated signal types revealed that the largest coordinate estimation errors were associated with conventional pulse signals, while the smallest errors were obtained for wideband LFM and long PCM waveforms. These findings indicate that waveform design plays a critical role in determining the overall performance of multistatic radar systems.

Overall, the obtained results demonstrate that advanced probing waveforms can substantially improve ranging accuracy and reduce target localization uncertainty. The observed improvement was particularly evident for signals possessing large effective bandwidths and favorable correlation characteristics.

Discussion

The obtained results demonstrate that the performance of a multistatic radar system is strongly dependent on the characteristics of the probing waveform. Since the ranging method relies entirely on accurate delay estimation, any factor influencing range measurement accuracy directly affects the quality of target coordinate estimation.

The relatively poor performance of conventional pulse signals can be explained by their limited bandwidth. In pulse radar systems, range resolution is determined primarily by pulse duration. Improving resolution therefore requires shorter pulses, which simultaneously reduces transmitted energy and may negatively affect detection performance. This fundamental limitation restricts the applicability of conventional pulse waveforms in systems requiring both long detection ranges and high localization accuracy.

The superior performance of LFM waveforms is associated with the pulse compression principle. By introducing frequency modulation within the pulse, it becomes possible to transmit a long-duration, high-energy signal while achieving the range resolution characteristics of a much shorter pulse after matched filtering. Consequently, LFM signals provide a favorable compromise between energy efficiency and ranging accuracy. The simulation results clearly indicate that

increasing the frequency deviation leads to a significant reduction in coordinate estimation errors, confirming theoretical predictions reported in previous radar signal processing studies.

PCM waveforms demonstrated comparable advantages due to their favorable correlation properties. The Barker-coded signal exhibited lower sidelobe levels than conventional pulse waveforms, resulting in more reliable delay estimation. The long Frank-coded waveform further improved performance because of its larger time-bandwidth product and enhanced processing gain. These characteristics contribute to more accurate range measurements and reduced coordinate uncertainty.

An important observation is that improvements in range estimation accuracy produce a greater overall effect in multistatic radar systems than in conventional monostatic radars. In a multistatic configuration, target coordinates are determined from the intersection of multiple range measurements. Consequently, even moderate improvements in individual range estimates lead to a substantial reduction in the resulting localization error. This effect becomes increasingly important when tracking small aerial targets, where precise coordinate information is required for reliable target classification and engagement.

The results also highlight the practical trade-off between localization accuracy and implementation complexity. Although wideband LFM and long PCM waveforms provide superior performance, their implementation requires more sophisticated signal generation, synchronization, and digital signal processing capabilities. Increasing signal bandwidth places additional requirements on analog-to-digital converters, waveform generators, processing hardware, and system synchronization. Therefore, waveform selection should consider both desired localization performance and available technological resources.

From an operational perspective, the obtained findings suggest that wideband LFM waveforms represent the most practical solution for modern multistatic radar systems. They provide high ranging accuracy, good energy efficiency, and relatively mature implementation technology. Long PCM waveforms may be particularly attractive in applications requiring improved interference resistance and enhanced correlation properties. Conventional pulse signals remain relevant for simple and low-cost radar systems but are less suitable for applications demanding high coordinate estimation accuracy.

Therefore, the conducted study confirms that waveform optimization is one of the most effective approaches for improving target localization performance in multistatic radar systems. The achieved results demonstrate that the use of wideband LFM and long phase-coded signals can significantly reduce coordinate estimation errors and enhance the overall effectiveness of ranging-based target localization.

Conclusions

This study investigated the influence of probing waveform characteristics on target coordinate estimation accuracy in a multistatic radar system employing the ranging method. The conducted analysis, mathematical modeling, and simulation experiments made it possible to evaluate the relationship between waveform parameters, range measurement accuracy, and the resulting localization performance of the radar system.

The literature review demonstrated that target coordinate estimation accuracy in multistatic radar systems is determined not only by the geometric configuration of radar positions but also by

the characteristics of the transmitted waveform. Modern radar systems increasingly employ wideband and coded waveforms to overcome the limitations of conventional pulse signals and to achieve higher ranging precision. However, the combined influence of waveform properties and ranging-based coordinate estimation in multistatic radar architectures remains insufficiently investigated.

A simulation model of a multistatic radar system was developed to assess the localization performance of different probing waveform types under identical operating conditions. The model incorporated range estimation based on signal delay measurements and target coordinate determination using measurements obtained from multiple spatially distributed radar positions. This approach enabled a comparative evaluation of waveform effectiveness with respect to coordinate estimation accuracy.

The obtained results confirmed that conventional pulse signals provide the lowest localization performance among the investigated waveform types. Their limited bandwidth results in relatively poor range resolution and consequently larger coordinate uncertainty regions. Although reducing pulse duration improves localization accuracy, the achievable performance remains significantly lower than that of modern modulated waveforms.

The study demonstrated that linear frequency modulated (LFM) signals provide substantial improvements in ranging and localization accuracy. Increasing the signal bandwidth through frequency modulation significantly reduces range estimation errors and decreases the spatial dispersion of estimated target coordinates. Among the investigated waveforms, wideband LFM signals exhibited the highest localization accuracy due to their large effective bandwidth and favorable pulse-compression properties.

PCM signals also demonstrated high effectiveness in multistatic radar applications. Barker-coded and Frank-coded waveforms provided improved correlation characteristics and reduced coordinate estimation errors compared with conventional pulse signals. Long phase-coded waveforms with large time-bandwidth products achieved localization performance comparable to that of wideband LFM signals while additionally offering improved sidelobe suppression and interference resistance.

The conducted analysis confirmed that signal bandwidth and time-bandwidth product are the primary factors influencing ranging accuracy in multistatic radar systems. Increasing these parameters leads to more accurate delay estimation, narrower correlation peaks, and reduced target localization uncertainty. Consequently, waveform optimization represents one of the most effective methods for improving coordinate estimation performance without requiring changes to the geometric configuration of the radar network.

An important finding of the study is that improvements in range measurement accuracy have a multiplicative effect on localization performance in multistatic radar systems. Since target coordinates are determined from multiple independent range measurements, even moderate reductions in individual ranging errors result in a significant decrease in the overall coordinate estimation error. This characteristic makes waveform optimization particularly valuable for multistatic radar architectures.

From a practical perspective, the results indicate that wideband LFM waveforms provide the most advantageous balance between localization accuracy, energy efficiency, implementation feasibility, and technological maturity. Long phase-coded signals constitute a promising alternative

for applications requiring enhanced correlation properties and increased resistance to interference. Conversely, conventional pulse waveforms are suitable primarily for low-complexity radar systems with moderate localization accuracy requirements.

Therefore, the research confirms that the application of advanced probing waveforms can significantly enhance the effectiveness of multistatic radar systems employing the ranging method. The obtained results may be used in the design and modernization of future radar systems intended for the detection, tracking, and localization of small aerial objects. Future research should focus on the investigation of adaptive waveform design, hybrid LFM–PCM signals, OFDM-based radar waveforms, and the influence of synchronization errors and electronic countermeasures on coordinate estimation accuracy in multistatic radar networks.

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Conflict of Interest

The author declares that there is no conflict of interest.

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Appendix

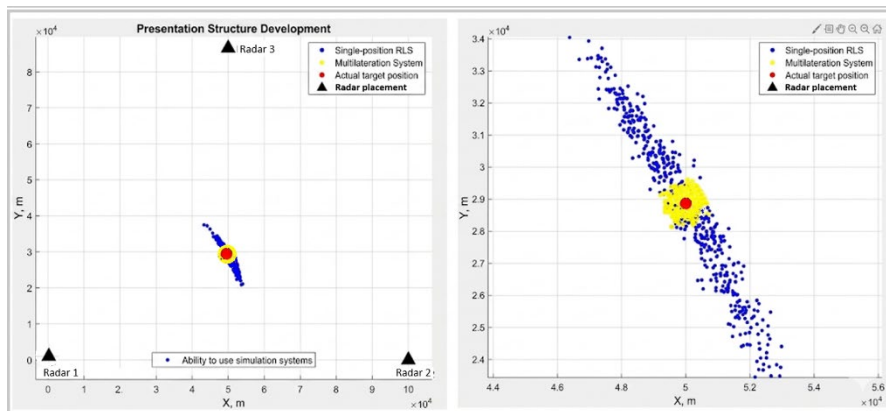


Figure 1. Results of modeling the process of determining the coordinates of the target in a three-position system with the location of the true target location in the center of the triangle (Source: compiled by the author)