Multisite Ultra-Wideband Radar Systems with Information Fusion: Some Principal Features

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Abstract -*Detection characteristics, resolution capability, and target coordinates measurement accuracy of Multisite Radar Systems (MSRSs) consisting of Ultra-Wideband (UWB) radars are analyzed. Two types of UWB radars are considered: using short carrier-free pulses and using pulses with carrier frequencies. Target radial dimensions are assumed to be much greater than range resolution cells of UWB radars, so that we have target range profiles at each radar. Noticeable advantages of MSRSs with UWB radars have been shown; especially when range profiles of a target may be expected to be equal with respect to all radars.*

Keywords: Multisite (multistatic) radar systems, ultra-wideband radars..

1 Introduction

There is a growing interest in Multisite Radar Systems, MSRSs (Multistatic Radars, Multiradar, or Netted Radar Systems) during the last years for both military and civilian applications (e.g., [1 – 5]). This may be explained by many significant advantages of MSRSs as compared with monostatic radars [6]. Among those advantages are: greater target detection range, higher target coordinates measurement and tracking accuracy in active and passive modes, higher resolution capability and others.

In recent years an increasing attention has been devoted to Ultra-Wideband (UWB) radars (e.g., [7 – 9]). Typical UWB radars are radars with very short carrier-free pulses, that is with very large *fractional bandwidth* (the bandwidth to mean frequency ratio). Advantages and drawbacks of such UWB radars are considered in many works (e.g., [7 – 9]). Here we note only one significant drawback: because of very short pulses, transmitted energy is, as a rule, small, so that UWB radars of this type have small detection range.

The salient feature of real UWB radars is their *large absolute signal bandwidth* Df_s permitting to resolve in range separate elements (scattering centers, "flare spots") of a target. Received signals turn out to be "range profiles" of targets. If this is accepted as a distinctive feature of UWB radars, then another a well-known type of radars may be referred to as UWB radars. Radars with absolute bandwidths 0.3, 0.5 GHz (that is with range resolution capabilities $\delta R = c/2Df_s$ = 0.5, 0.3 m) providing target range profiles appeared as early as 30-40 years ago (e.g., [10, 11])). However, because radar range resolution capability does not depend on signal carrier frequency, all such radars have usually high carrier frequencies, so that their fractional bandwidth is not large, as a rule, not more than 10%.

A large absolute bandwidth of such radars can be achieved also by using very short modulating pulses. The main advantage of such radars is the absence of range sidelobes (as with short pulse carrier-free radars). However, though such radars may have antennas with narrow directivity patterns (unlike short pulse carrier-free radars where such antennas are much more difficult to construct), low transmitted pulse energy leads to small detection range. Therefore, if a large detection range is required, sufficiently long pulses are conventionally used with frequency modulation or phase coding inside each pulse (including frequency modulation by random noise [12]), and special techniques are employed to minimize range sidelobes of compressed signals in receivers.

Thus, UWB radars of both types (with carrier-free pulses and with carrier frequencies) have, as a rule, large absolute bandwidths. Taking into account that some principal characteristics of MSRSs depend essentially on the waveform bandwidth [6], it is important to consider principal features of MSRSs based on UWB radars. It may be expected that such MSRSs have significant advantages over MSRSs with conventional narrow-band radars and good prospects in a wide range of applications.

In this paper, we consider only detection characteristics, resolution capability and angle coordinates measurement accuracy of UWB MSRSs.

Since absolute radar bandwidths are important for the purposes of this paper, both types of UWB radars will be considered together. Their differences will be taken into account only if necessary.

2 Detection characteristics

It is clear that resultant detection characteristics of UWB MSRSs are determined by energy characteristics of UWB radars and by energy gain as a result of joint processing in MSRSs (information fusion). As was mentioned above, thanks to large signal bandwidths, Df_s, of UWB radars, most targets turn out to be extended ones (their radial dimensions are greater or much greater than radar range resolution cells $c/2Df_s$). In this situation, detection characteristics depend significantly on specific target range profiles and signal processing of received signals.

Let us consider UWB radars of the second type (with a large absolute and small fractional bandwidth). The determining feature for signal processing at such radars is the fact that *the signal waveform received from each point-like target is known* because it is the same as the waveform of transmitted signals. Optimal processing consists of coherent filtration matched to reflections from each flare spot of a target and then to incoherent integration along its range profile (e.g., [13]).

When all or nearly all flare spots of a target are resolved in range, received signals do not fluctuate or fluctuate very weakly. Let n_0 be the total number of range resolution cells in a target range profile. Then the output quantity (which is to be compared with a threshold) is a sum of $2n_0$ uncorrelated (under certain conditions) random variables with Rice or Rayleigh probability distributions. Rice distribution corresponds to those range resolution cells of a range profile where signals from flare spots are present, and Rayleigh distribution corresponds to cells with noise alone. We assume here for simplicity and for obtaining the best possible results, that n_0 is known for all UWB radars. If it is not so, different multichannel structures may be used with certain energy losses [13, 14].

If $2n_0$ is large enough, these output quantities may be considered as Gaussian variables with certain means and variances depending on the specific range profiles.

It may be expected that two opposite factors influence UWB radar detection characteristics as compared with narrowband radars. For fixed energy of received signals (or average energy of fluctuating signals), the bandwidth widening leads, on the one hand, to energy gain (for large values of detection probability) because of fluctuations elimination, and, on the other hand, to energy losses of incoherent (relative to coherent) integration.

For radars using very short, carrier-free pulses, the determining feature for signal processing is *uncertainty of received signal waveform even from a point-like target.* Because of large fractional bandwidth, signal waveforms change significantly in the process of transmission, propagation, reflection and reception (e.g., [7,8]).

The optimal detection algorithm (according to the generalized maximum likelihood criterion) for such radars was synthesized in [14]. This algorithm takes into account that the Pulse Repetition Period (PRP) is usually known. Besides, range profiles of a target may be considered as having the same (though unknown) form in several, for example, M, successive PRPs. The value of M depends on many factors (including the character of target motion) but for sufficiently small PRP, at least $M \geq 2$ may be assumed. (It should be noted that because of mentioned above small maximum range of such radars, their PRPs are usually short). The optimum algorithm has the form [14]:

$$L = \int_0^{t} \left[\sum_{k=0}^{M-1} x(t + t_d + kT_r) \right]^2 dt \gtrless u \qquad (2)$$

where t is the duration of the expected signal (range profile) in time ($t = n_0/Df_s$), M is the number of successive range profiles assumed to have the same form, $x(t)$ is the overall received signal (signal plus noise or noise alone), t_d is the time delay determined by target range, T_r is the PRP of the radar. As can be seen from Eq. (2), the assumption of unchanged range profiles of a target during successive M PRPs, has led to "coherent" summation of M corresponding portions of input signals. The energy of this sum is to be compared with a threshold. Typical detection characteristics of a narrowband radar and UWB radars of both types for the same target are shown in Fig. 1.

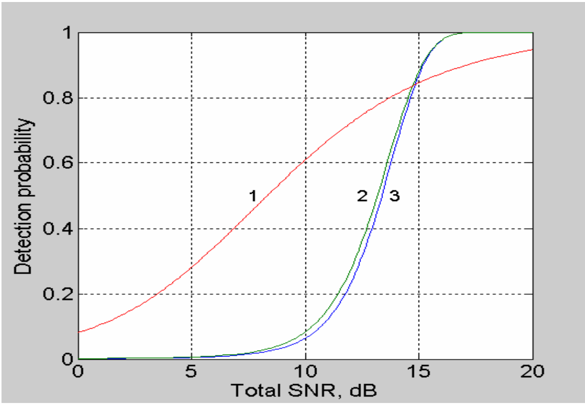

Fig. 1. Detection characteristics of the narrowband radar (curve 1), the UWB radar with carrier-free pulses (curve 2), the UWB radar with carrier (curve 3); $M = 2$; $P_{fa}=10^{-3}$.

These curves are calculated on the assumptions that: 1) amplitude fluctuations of narrowband received signals are completely correlated in neighbor PRPs and subject to Rayleigh probability distribution; 2) total number of target range resolution cells for UWB radars, n_0, is known and equal to 32, so that total number of output signal samples is equal to $2n_0 = 64$; 3) all flare spots of the target are resolved in range by UWB radars of both types; 4) the range profiles represent signals from $N_{fs} = 16$ flare spots with the following distribution of Signal-to-Noise Ratios (SNRs): each signal from 2 flare spots has SNR equal to 12% of the total SNR, each signal from 8 flare spots has SNR equal to 7% of the total SNR, each signal from 4 flare has SNR equal to 4%, and each signal from 2 flare spots has SNR equal to 2% of the total SNR; range side lobes are ignored; 5) the total SNR ($2E_s/N$) at the UWB radars is equal to the average SNR (E_{sav}/N) at the narrowband radar with fluctuating signals; 6) the false alarm probability $P_{fa} = 10^{-3}$.

Detection characteristics do not depend on the specific arrangement of resolved flare spots along a target.

It can be seen that UWB radars with short carrier-free pulses and with carrier frequencies have almost the same detection characteristics (for the assumed parameters). The point is that high effective coherent processing matched to signals reflected from each flare spot is possible for radars with carrier frequencies but then incoherent signal integration after envelope detection is not so effective. For radars with short carrier-free pulses, unknown waveforms received from flare spots do not permit using coherent matched filtration but this may be compensated by "coherent" summation of input signals during M PRPs. For $M = 2$ we have a balanced situation.[1]

As was to be expected, these radars have energy gain over narrowband radars for high detection probabilities ($P_d > 0.8$). Energy loss for $P_d = 0.5$ is about 5 dB. Note that for a target with doubled n_0 and N_{fs} and the same total SNR, additional loss of 0.7 dB takes place. It means that when all flare spots are resolved, so that signal fluctuations are eliminated, further increase of range resolution leads only to additional energy losses (higher threshold is necessary to keep the allowed P_{fa}).

Let us pass now to MSRSs. As was shown in [6], detection characteristics enhancement in a narrowband MSRS as compared with a monostatic radar, depends significantly on correlation degree of signal fluctuations at the inputs of spatially separated stations. For completely correlated fluctuations, the main role plays the increase of total received signal energy.

When UWB radars are used in MSRSs, and all or nearly all target flare spots are resolved in range (so that received signals do not fluctuate), joint signal processing leads also to the increase of total received signal energy.

As will be shown below, for radars with large bandwidths, MSRSs with small baselengths between spatially separated stations (compared with expected target range) may be used, which are much simpler than MSRSs with large baselengths. Under this condition, signal energy received by several spatially separated UWB radars with equal characteristics may be considered to be equal if targets are at the approximately equal distances from radars. This is the more so, since resolved target flare spots have usually broad directivity patterns.

As far as specific forms of range profiles are concerned, we consider two cases: equal range profiles and different range profiles. When the baselengths of MSRSs are small enough to have *the same (but unknown) range profiles of a target at all UWB radars*, then there is no difference between joint signal processing of successive PRPs at each station and interstation processing. For UWB radars with carrier, incoherent summation of radar outputs is optimal. For UWB radars with short carrier-free pulses we have optimum detection algorithm from Eq. (2):

$$L = \int_0^t \left[\sum_{i=1}^{m} \sum_{k=0}^{M-1} x(t + t_d + kT_r) \right]^2 dt \underset{<}{\geq} \text{u}. \qquad (3)$$

Typical detection characteristics are shown in Fig. 2 for the MSRS with $m = 3$ equal radars. The radars are the same as in Fig. 1 (narrowband, UWB with short carrier-free pulse, and UWB with carrier). For the MSRS with narrowband radars, fluctuations are assumed to be completely correlated in time and in space. At each station two repetition periods are jointly processed ($M = 2$). This situation is equivalent to a monostatic radar processing echoes of $M = 6$ successive periods.

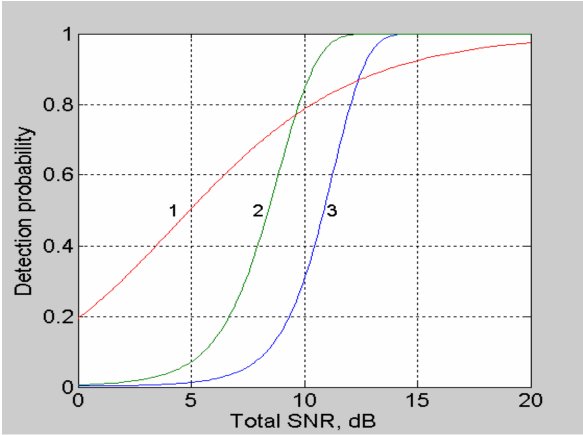

Fig. 2. Detection characteristics of the MSRS with 3 types of radars, notation as in Fig. 1; $m = 3$; $M = 2$; equal unknown target range profiles at all radars; $P_{fa} = 10^{-3}$.

It is seen that the MSRS consisting of UWB radars with short carrier-free pulses have better detection characteristics than the MSRS based on UWB radars with carrier frequencies because of "coherent'' signal processing of all the 6 received signals. Comparing with Fig. 1, one can see that energy gain caused by information fusion in the MSRS is of the order of 3 dB for both the UWB radar with carrier frequency and the narrowband radar and reaches up to 5 dB for the UWB radars with short carrier-free pulses. Advantages over the narrowband radars take place when detection probability $P_d \geq 0.8$.

Much greater energy gain may be obtained in a MSRS with so called cooperative signal reception [6]. In this case all radars may receive and process target echoes when a target is illuminated not only by "own" but by any other transmitter of the MSRS. If range profiles are equal at the inputs of all the m receivers, the optimum detection algorithm for MSRSs consisting of UWB radars with short carrier-free pulses takes the form:

$$L = \int_0^t \left[\sum_{i=1}^{m^2} \sum_{k=0}^{M-1} x(t + t_d + kT_r) \right]^2 dt \underset{<}{\geq} \text{u}. \qquad (4)$$

When $m = 3$, and echoes of $M = 2$ repetition periods are processed at each radar, we have joint processing of 18 received signals ("coherent" for UWB radars with short carrier-free pulses and incoherent for UWB radars with carrier). The corresponding detection characteristics are presented in Fig. 3. It can be seen that energy gain of the MSRS consisting of UWB radars, as compared with the corresponding monostatic UWB radar (see Fig. 1), is greater by about 10 dB for the radar with short carrier-free pulses and about 5 dB for the radar with carrier frequencies. A noticeable energy advantage over the MSRS with narrowband radars begins for detection probability exceeding 0.75.

[1] Coherent summation of M successive signals from a motionless target is possible theoretically at UWB radars with carrier frequencies too. However, since a carrier frequency is usually at least by an order greater than the bandwidth, coherent summation is much more difficult than at the UWB radars with carrier-free pulses.

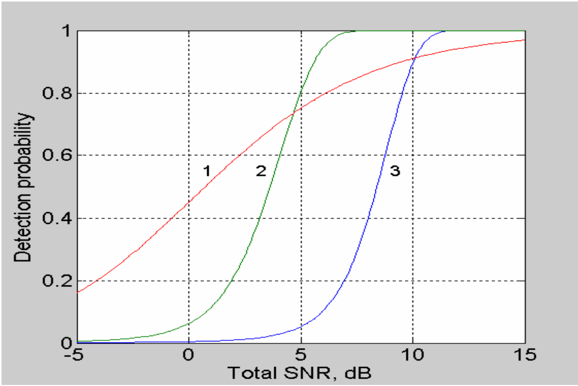

Fig. 3. Detection characteristics of the MSRS, notation as in Fig. 1; m = 3; cooperative signal reception; M = 2; equal target range profiles at each radar; P_{fa}=10^{-3}.

When a target provides *different unknown range profiles relative to spatially separated stations*, and cooperative signal reception does not used, optimal interstation processing even for UWB radars with short carrier-free pulses is reduced to summation of energy estimates obtained at all stations:

$$L=\sum_{i=1}^{m}\frac{1}{N_i}\int_0^{t_i}\left[\sum_{k=0}^{M-1}x_i(t+t_{di}+kT_r)\right]^2 dt \gtrless u. \qquad (5)$$

It means that interstation processing becomes incoherent. This leads to energy losses (as compared with “coherent” processing). Typical detection characteristics for the same MSRS as in Fig. 2 but for different unknown range profiles relative to all the 3 stations are shown in Fig. 4.

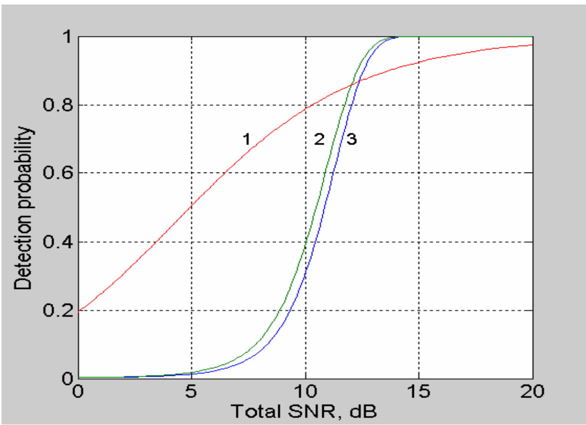

Fig. 4. Detection characteristics of the MSRS, notation as in Fig. 1; m = 3; M = 2; different unknown target range profiles at each radar; P_{fa}=10^{-3}.

It can be seen that energy gain of the MSRS consisting of UWB radars with short carrier-free pulses is much less than in the case of equal range profiles because of the incoherent interstation signal processing. MSRSs with UWB radars of both types have almost the same detection characteristics.

For cooperative signal reception, and not too large baselengths between stations, a target range profile received by the i-th station when a target is illuminated by the j-th station may be assumed to be equal to the target range profile received by the j-th station when the same target is illuminated by the i-th station. Then we have M equal range profiles at each station and M pairs of equal range profiles at $m(m-1)/2$ different stations. For m UWB radars with short carrier-free pulses and equal technical characteristics the optimum detection algorithm is:

$$L=\sum_{i=1}^{m}\int_0^{t_i}\left[\sum_{k=0}^{M-1}x_i(t+t_{di}+kT_r)\right]^2 dt+$$

$$\sum_{i=1}^{m-1}\sum_{j=i+1}^{m}\int_0^{t_{ij}}\left[\sum_{k=0}^{M-1}x_{ij}(t+t_{dij}+kT_r)+x_{ji}(t+t_{dji}+kT_r)\right]^2 dt \gtrless u. \qquad (6)$$

Corresponding detection characteristics for m = 3 and M = 2 are shown in Fig. 5.

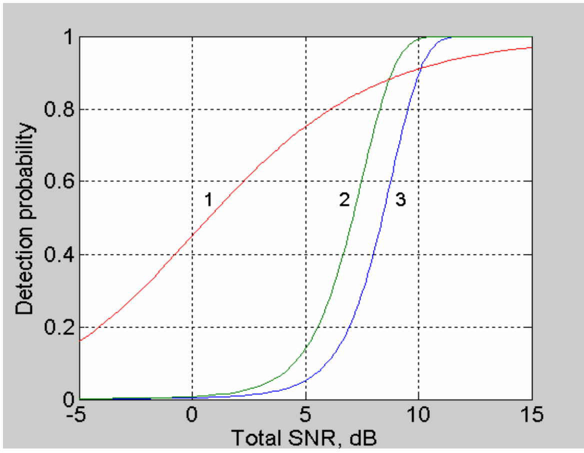

Fig. 5. Detection characteristics of the MSRS, notation as in Fig. 1; m = 3; cooperative signal reception; M = 2 equal unknown target range profiles at each radar and M = 2 pairs of equal range profiles at m = 3 different radars; P_{fa}=10^{-3}.

It is seen that the detection characteristic for the MSRS consisting of radars with short carrier-free pulses takes an intermediate position in comparison with corresponding characteristics of Fig. 3 and Fig. 4. Energy gain as compared with a monostatic radar is of 5…6.5 dB. Advantages over the MSRS with narrowband radars begin when detection probability is greater than 0.85…0.9.

3 Angle resolution capability of active MSRSs

As is well known, angle resolution capability of a monostatic radar is determined by the beamwidth of its antenna. Therefore, linear resolution capability in cross-range direction of a UWB radar is usually much worse than resolution capability in range.

It may seem that high angle resolution capability itself is of no practical significance for UWB radars having very high range resolution capability because it is sufficient to resolve a target in at least one coordinate (or signal parameter).

However, as can be seen from Fig. 7, it is not so.

A region within the intersection of antenna main beams of two UWB radars is presented in Fig. 7. Range resolution cells of both radars are shown by corresponding curves. In spite of very high range resolution capability, radar 1 cannot resolve two targets. This radar receives two partly overlapping range profiles of both targets. At the same time, radar 2 receives two separate range profiles, that is, can resolve the targets. This is a result of an angle distance between targets, and may be treated as a capability of MSRSs to resolve targets in angle within the main beams of receiving antennas.

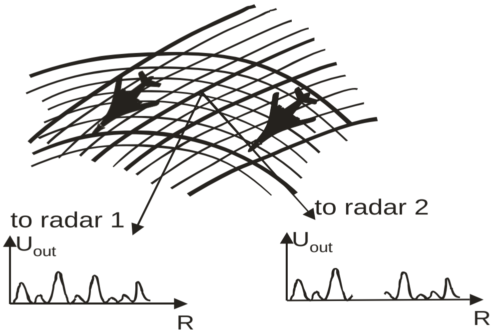

Fig. 7. Two targets are not resolved by radar 1 but are resolved by radar 2.

It is easy to show that if the target range, R, is at least by several times greater than the effective baselength, L_{eff}, between radars, the equivalent angle resolution capability, dq, of the system (relative to radar 1) is:

$$dq \text{ » } dR/L_{eff} = c/2Df_s L_{eff} \quad (7)$$

where $dR=c/2Df_s$ is the range resolution cell of radar 2. The effective baselength, L_{eff}, is the length of the baseline projection on the plane orthogonal to the bisector of the angle between directions from a target to stations of interest [6].

If radar 2 is replaced by a receiving station, we have instead of Eq. (7)

$$dq \text{ » } dR_S/L_{eff} = c/DfL_{eff}. \quad (8)$$

Eqs. (7) and (8) can be referred to as the beamwidth of a Resultant Directivity Pattern (RDP) of a pair of radars or a pair of receiving stations, respectively [6]. It can be seen that this beamwidth (the equivalent angle resolution capability) is determined by the product of the effective baselength and the radar bandwidth. It follows from Eqs. (7) and (8) that a MSRS with UWB radars having very large values of Df_s, can provide very high angle resolution capability or allow to decrease drastically the baselength between stations.

Example 1. Let Df_s= 500 MHz. Then with L_{eff} = 1 km we have from (7) and (8) , respectively: dq » $3\cdot10^{-4}$ rad » 1' and dq » $6\cdot10^{-4}$ rad » 2'. It means that the cross-range resolution capability, $dR_{\perp}$» 3 m and $dR_{\perp}$ » 6 m, respectively, at the range R = 10 km. If a UWB MSRS is designed for short target ranges (as is the practice for UWB radars with short carrier-free pulses), of the order of 10…20 m, then for the same cross-range resolution capability, the effective baselength, L_{eff}, may be reduced down to 1…2 m.

4 Angle resolution capability of passive MSRSs

Passive MSRSs are used for detection and coordinate measurement of radiation sources.

Resolution capability of hyperbolic passive MSRSs is determined by the width of the envelope's main lobe of the received signal mutual correlation function. This main lobe width can be expressed in Time Difference Of Arrival (TDOA) $dt \approx 1/Df_s$ as well as in range difference $dDR \approx c/Df_s$. For the RDP of two receiving stations Eq. (8) is valid if $R/L_{eff} >> 1$.

If a hyperbolic MSRS consists of UWB receiver stations (and received radiation is also UWB), we may obtain very high angle resolution capability or allow to decrease drastically the baselength between stations (as with active UWB radars).

Eq. (8) is valid for passive hyperbolic MSRSs. Hence the above *Example 1* illustrates the attainable angle resolution capability for such a passive UWB MSRS too.

5 Accuracy of angle coordinates estimation

As a rule, target position determination by an UWB monostatic radar is much less accurate in cross-range direction (using angle coordinate measurements) than in down-range one. A MSRS is capable to estimate three target coordinates using only range (or range-sum) measurements from several spatially separated monostatic radars (or transmitting and receiving stations)(e.g., [6]).

Let us consider firstly a point-like target. Fig. 8 shows sections of two error ellipsoids obtained as a result of target position measurement by each of two 3D radars.

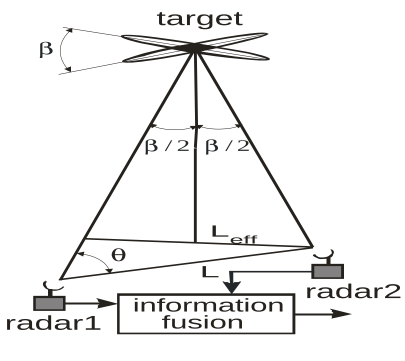

Fig. 8. Target range measurements in a MSRS increase the angle coordinate estimation accuracy.

Each ellipsoid is usually flattened like a "pancake". The intersection of those ellipsoids may be considered as a resultant error body after information fusion from two radars. It can be seen, that there is a noticeable gain in the target position estimation accuracy mainly due to the range measurements. It may be treated as an increase of the angle coordinate estimate accuracy as compared with a monostatic radar. For rough calculations of angle accuracy provided by range measurements at each spatially separated pair of radars, the following approximate expression is convenient to use:

$$s\,(q\,) = s\,(R\,)\sqrt{2}\,/\,L\,sinq \approx s\,(R\,)\sqrt{2}\,/\,L_{eff}\ . \qquad (9)$$

When one or two radars are replaced by receiving stations (in the latter case a transmitting station is separated from both receiving ones), we have instead of Eq. (9):

$$s\,(q) = s\,(R_S\,)\sqrt{2}\,/\,L\sin q \approx 2s\,(R)\sqrt{2}\,/\,L_{eff}\ . \qquad (10)$$

In Eqs. (9, 10) $s\,(q)$ is the r.m.s. error of angle estimation in the plane passed through the target and both radars;? $s\,(R)$ and $s\,(R_S\,)$ are the r.m.s. errors of range and range-sum measurements (assuming all these errors to be statistically independent at different stations with equal r.m.s. values); L is the baselength; L_{eff} is the effective baselength. Eqs. (9, 10) are derived under "small baselength" condition (target range $R >> L_{eff}$) but it may be used for rough calculations even when R>(2–3) L_{eff}.

It follows from Eqs. (9, 10) that with range measurements of high accuracy (that is, if wideband signals are used), and if effective baselengths are sufficiently large, the angle estimation r.m.s. error $s\,(q)$ may be much less than that of a usual bearing measurement by a monostatic radar with the help of its antenna.

For a usual narrowband radar, the r.m.s. error of range measurements is a fraction of the range resolution capability:

$$s\,(R) = kdR = kc\,/\,2Df_s \qquad (11)$$

where $k < 1$ depends on SNR.

However, for UWB radars, most targets turn out to be extended ones. In this case it is important, how to use the received range profiles for target range measurement.

For a monostatic UWB radar the target range measurement technique is not too important because almost any technique provides sufficient accuracy for practice. However, these techniques are important for UWB MSRSs, which angular accuracy depends directly on range measurement accuracies of radars [Eqs. (9, 10)].

The simplest situation takes place if it is possible to extract and identify a reflected signal from the same flare spot in range profiles of all stations. Then this flare spot may be considered as a point-like target, and Eqs. (9 – 11) are valid. If such a flare spot is impossible to extract and identify, the attainable range measurement accuracy depends on the similarity of range profiles received by all stations.

Let these range profiles be equal. In this case any point of the profile (but the same point at all stations) may be chosen for target range measurement. It may be, for example, the centers of these range profiles. This center may be calculated using range measurements of all flare spots of the profile with the subsequent averaging of measurement results (better weighted proportionally to SNR values). Noise errors of such range measurement may be less than those of measurement using only one flare spot because noise errors for different flare spots are statistically independent. Eqs. (9, 10) may also be used in this situation but the coefficient k in Eq. (11) may be smaller than in the case of one flare spot. It is also possible to average angle estimates obtained from range measurements for different pairs of equal flare spots.

Example 2. Let us consider the same UWB MSRS as in *Example 1* and assume the coefficient k in Eq. (11) to be equal to 0.3. Then for the effective baselength L_{eff} = 1 km we have from Eqs. (9, 11) $s\,(q) \approx 1.3{\cdot}10^{-4}$ rad. ≈ 0.44' and from Eqs. (10, 11) $s\,(q) \approx 2{,}5{\cdot}10^{-4}$ rad. ≈ 0.87'. The linear r.m.s. error in cross-range direction at the range R = 10 km is only 1.3 m and 2.5 m, respectively! For short range UWB radars at the target range 10…20 m, the same linear cross-range r.m.s. errors may be achieved with the effective baselength, L_{eff}, reduced down to 1…2 m.

There are several sources of systematic and random errors, which may contribute into resultant range measurement errors, especially if noise errors are so small. However, when target range measurements are used for target angle coordinate estimation in a MSRS, equal systematic and mutually correlated (at different stations) errors may be almost completely eliminated.

Quite another situation takes place when range profiles received from the same target by spatially separated stations are essentially different. Some additional errors for any SNR may occur depending on specific range measurement technique. These errors may be as large as a fraction of each range profile length, which lead to angle errors significantly greater than those from Eqs. (9 – 11). However, as was mentioned above, UWB MSRSs may, as a rule, have small baselengths between stations, so that the angle between directions from a target to spatially separated stations may also be small. Under this condition, range profiles received by different stations from the same target may be expected to be quite similar.

As was mentioned above, Eqs. (9, 10) are valid for a plane passed through the target and both radars. High accuracy of target position determination in 3D space by only range measurements in a UWB MSRS is possible to achieve if the MSRS consists of at least three radars [15]. Having measured target ranges from two radars, we obtain two spherical surfaces. Their intersection is a circumference on which the target must lie (in the absence of errors). However, each point of this circumference is determined by two angles. It means that a MSRS consisting of two UWB radars and using only target range measurements, cannot determine even one target angle coordinate because of the second angle coordinate uncertainty (for example, cannot determine azimuth because of elevation angle uncertainty).

Let us assume that range measurement errors at all radars are reduced to mutually uncorrelated random values. It means that all systematic errors are eliminated. Under this condition, covariance matrices of Resultant Target Coordinate Estimates (RTCEs) obtained after optimal measurement fusion may be used as characteristics of Target Localization Accuracy (TLA) [6, 15]. The optimality is understood here according to least mean square criterion or maximum likelihood criterion if errors are Gaussian.

Let target spherical coordinates $a = (R,\ b,\ e)^T$ in a reference coordinate system (range, azimuth, and elevation angle) be estimated by range measurements of m spatially separated radars, so that we have target measurement vector $\hat{x} = (\hat{R}_1,\ldots,\hat{R}_m)^T$. Since radar positions are known, all relationships between true values of x and a are known too, that is $R_i = h_i(R, b, e)$, $i = \overline{1,m}$, or, more compactly, $x = \mathbf{h}(\mathbf{a})$.

The covariance matrix $?_{\mathbf{a}}$ of a RTCE $\hat{a}$ may be expressed as follows (e.g., [6]):

$$?_{\mathbf{a}} = \overline{(\hat{a} - \bar{\hat{a}})(\hat{a} - \bar{\hat{a}})^T} = (\mathbf{H}^T \mathbf{B}_x^{-1} \mathbf{H})^{-1} \qquad (12)$$

where $\mathbf{B}_x^{-1}$ is the covariance matrix of local measurements $\hat{x}$ received from spatially separated radars; $\mathbf{H} = \left\| \partial R_i / \partial R \quad \partial R_i / \partial b \quad \partial R_i / \partial e \right\|$ is the matrix of derivatives of functions $R_i = h_i\ (R,\ b,\ e)$, $i = \overline{1,m}$, with respect to target coordinates. All derivatives are taken at the point of true target coordinates a . Equation (12) offers a general way for UWB MSRSs accuracy analysis.

Let the first radar of an UWB MSRS be placed at the coordinate system origin. This Central Radar (CR) number "0" measures the target range directly $R_0 = R$, while the i-th ($i = \overline{1,m}$) Spatially Separated Radar (SSR) measures the target range R_i relative to its position at the point with reference coordinates (L_{ai}, $ß_{ai}$, e_{ai}). L_{ai} is the baselength between the CR and the i-th SSR. Range measurement errors (r.m.s. values) may be denoted as $s(R)$ of the CR and $s(R_i)$ of the i-th SSR. The most interesting are the resultant azimuthal and elevation angle r.m.s. errors, $s_{res}(ß)$ and $s_{res}(e)$.

It can be shown that all derivatives of measured values R_i with respect to target coordinates R, $ß$, e [matrices **H** in Eq. (12)] depend only on the differences $Dß_i = ß - ß_{ai}$. It means that the accuracy of RTCEs may be analyzed as a function of $Dß_i$.

Example 3. Let us consider a UWB MSRS consisting of three equal radars from *Example 1* and *Example 2*: one CR and two SSRs with Df_s = 500 MHz and $s(R) = s(R_1) = s(R_2)$ = 0.1 m. For simplicity and transparency of results, we assume $e_{a1} = e_{a2} = 0$, that is all three radars lie in the horizontal plane. Let $L_{a1} = L_{a2}$ = 1 km. The baselines of two SSRs assumed to be orthogonal to each other, i.e. $ß_{a1} - ß_{a2} = \pm p/2$. Let $ß_{a1} = 0$, $ß_{a2} = -p/2$. Then $Dß_1 = ß - ß_{a1} = ß$, $Dß_2 = ß - ß_{a2} = ß + p/2$. Target elevation angle is 30°, target range R= 10 km.

Resultant r.m.s. azimuthal and elevation angle errors are shown in Fig. 9 and Fig. 10, respectively.

It can be seen, first of all, that these errors are very small as compared with angle errors of usual monostatic radars.

With the baselengths $L_{a1} = L_{a2}$ = 1 km only, these angle errors provide linear cross-range errors at the range R = 10 km in azimuthal direction $s(R_{\perp\beta}) \approx 1.1\ldots2.1$ m and in elevation angle direction $s(R_{\perp\varepsilon}) \approx 2.0\ldots3.7$ m.

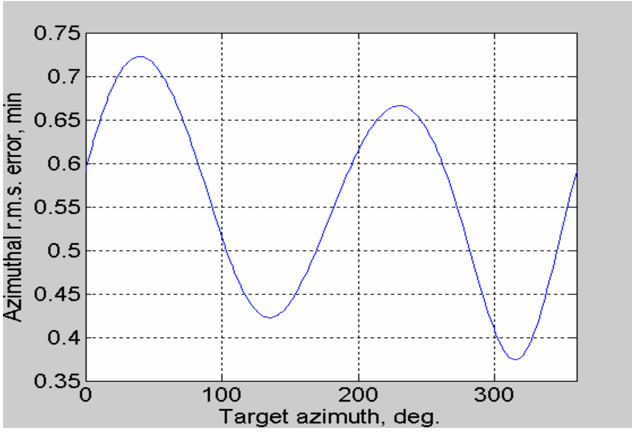

Fig. 9. Target azimuthal r.m.s. error, $s_{res}(ß)$, as a result of target range measurements in an UWB MSRS with 3 radars (*Example 3*).

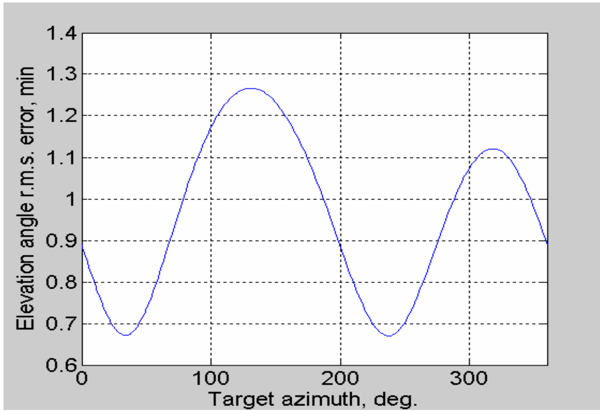

Fig. 10. Target elevation angle r.m.s. error, $s_{res}(e)$, as a result of target range measurements in an UWB MSRS with 3 radars (*Example 3*).

The same linear cross-range errors may be obtained for short range radars at the range 10 m if the baselines between stations are decreased down to $L_{a1} = L_{a2}$ = 1 m (though angle errors increase by 1000 times).

Error variations depending on target azimuth are caused by variations of effective baselengths. To decrease error variations, more radars are necessary with symmetric configuration about the coordinate system origin.

Higher elevation angle errors (than azimuthal ones) are caused by the decrease of corresponding effective baselengths for target elevation angle 30° and horizontal MSRS.

Angle measurement accuracy of the same order as for active UWB MSRSs, may be achieved by passive hyperbolic UWB MSRSs with correlation signal processing.

6 Conclusions

Detection, resolution and measurement accuracy characteristics of MSRSs consisting of UWB radars have been analyzed.

From the point of view of optimum signal processing for target detection, there is a significant difference between two types of UWB radars: 1) radars with short carrier-free pulses (with large fractional bandwidth), and 2) radars using ultra-wideband pulses with carrier frequency (with relatively small fractional bandwidth, for example with internal frequency modulation or phase coding). For the second type, the received waveform from a point-like target is known, and this knowledge is used for a coherent portion of signal processing. For the first type, the received waveform even from a point-like target is unknown.

Resolution and measurement accuracy characteristics are determined by the absolute radar bandwidth and MSRS configuration regardless (approximately) of the UWB radar type.

1. Detection characteristics are considered for UWB MSRSs of both types. It is shown that elimination of received signal fluctuations leads to noticeable energy gain and energy loss at high and low detection probabilities, respectively, for both monostatic UWB radars and UWB MSRSs, as compared with narrowband radars and narrowband MSRSs.

2. Significant energy gain can be achieved by UWB MSRSs with short carrier-free pulses if target range profiles received by different stations may be expected to be equal, especially for cooperative signal reception because of “coherent” interstation processing. For different range profiles at spatially separated stations, interstation processing must be incoherent, and detection characteristics of short pulse carrier-free UWB radars near to those of UWB radars with carrier frequencies.

3. In spite of high range resolution, there are situations where a monostatic UWB radar cannot resolve targets, especially when its antenna beamwidth is broad. UWB MSRSs can provide very high angle resolution capability even when baselines between stations are small.

Hyperbolic passive UWB MSRSs with correlation signal processing have angle resolution capability of the same order.

4. UWB MSRSs can provide very high estimation accuracy of target angle coordinates using only target range measurements, if it is possible to identify signals from the same target flare spot at different radars or range profiles received by those radars are equal (or almost equal). At the same time, if range profiles received by different radars of a UWB MSRS are essentially different, additional errors may occur in range measurements of the order of a fraction of target radial length. In this case target angle errors may increase significantly. To avoid such situations, angles between directions from a target to different radars of an UWB MSRS should be decreased.

The possibility of target angle coordinates estimation with high accuracy through range measurements by UWB MSRSs is of great practical importance because UWB radars have usually broad antenna beamwidth (especially UWB radars with short carrier-free pulses).

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