Target Detection by Multisite Ultra-Wideband Radar Systems with Information Fusion

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Abstract -Detection characteristics of Multisite Radar Systems (MSRSs) consisting of Ultra-Wideband (UWB) radars are analyzed. Two types of UWB radars are considered: using pulses with carrier frequencies and using short carrier-free pulses. Target radial dimensions are assumed to be much greater than range resolution cells of UWB radars, so that each radar receives range profiles of a target. 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.

Key-words: 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. As it was shown in [6], many important characteristics of MSRSs strongly depend on signal bandwidths: the wider bandwidth, the better these characteristics.

In recent years an increasing attention has been devoted to Ultra-Wideband (UWB) radars (e.g., [7 – 9]). Though not generally accepted, the following formal definition of the UWB radar is used by many specialists [7, 8]:

$$h = (f_{\text{upper}} - f_{\text{lower}})/(f_{\text{upper}} + f_{\text{lower}}) \geq 0.25. \qquad (1)$$

Here f_{upper}, f_{lower} are the upper and the lower frequencies, respectively, of signal processed.

Typical UWB radars corresponding to the above definition are radars with very short carrier-free pulses. 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.

Though it is not necessary follows from the above definition, 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 $c/2Df_s$ 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* (the bandwidth to carrier frequency ratio) 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 frequencies and carrier-free) have, as a rule, large absolute bandwidths. Taking into account that some principal characteristics of MSRSs depend essentially on the waveform bandwidth, 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.

We consider in this paper only detection characteristics of UWB MSRSs.

2 Detection Algorithms

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 received signal processing.

Let us consider UWB radars of the second type (with large absolute and small fractional bandwidth). The determining feature for signal processing at such radars is the fact that *the received signal waveform reflected by a 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 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. The output value (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. Here n_0 is the total number of range resolution cells in a range profile. 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 (especially when most of range resolution cells are with signals) these output values 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 (or average energy) of received 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 because of incoherent summation and the necessity of higher threshold for keeping fixed resultant false alarm probability.

For radars of the first type (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 very large fractional frequency, 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].

The 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 $M > 1$ may be assumed. (It should be noted that because of small maximum range of such radars mentioned above, their PRPs are usually short). The optimum algorithm may be written as follows:

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

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.

3 Detection Characteristics

Typical detection characteristics of a narrowband radar and UWB radars of both types for the same target are shown in Fig. 1. These curves are calculated on the assumptions that: 1) two echoes (of

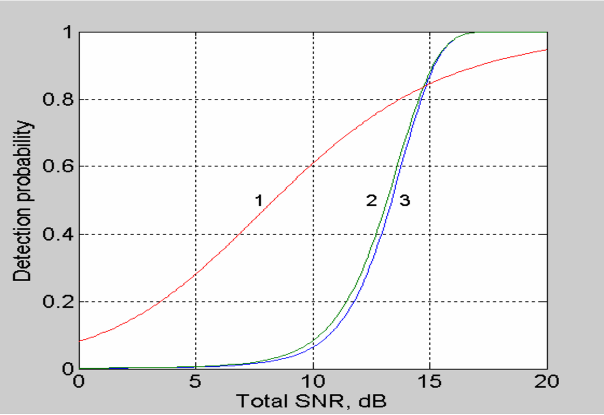

Fig. 1. Detection characteristics of a narrowband radar (curve 1), an UWB radar with carrier-free pulses (curve 2), an UWB radar with carrier (curve 3); $M = 2$; $P_{fa}=10^{-3}$.

two neighbor periods) are jointly processed ($M = 2$); 2) amplitude fluctuations of narrowband received signals are subject to Rayleigh probability distribution, and these fluctuations are completely correlated in neighbor PRPs; 3) 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 $2n_0 = 64$; 4) all flare spots of the target are resolved in range by UWB radars of both types; 5) the range profile 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; 6) the total SNR ($2E_s/N$) for the UWB radars is equal to the average SNR ($E_{s\ av}/N$) for the fluctuating narrowband signals; 7) the false alarm probability is $P_{fa} =10^{-3}$.

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

It can be seen that UWB radars with carrier frequencies and with short carrier-free pulses have almost the same detection characteristics (for the assumed parameters). Coherence processing matched to signals reflected from all flare spots is possible in radars with carrier frequencies but incoherent signal summation after envelope detection is not so effective. Unknown waveform received from each flare spot does not permit using matched filtration in radars with short carrier-free pulses but this may be compensated by “coherent” summation of input signals. 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. It is interesting to 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.

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. Joint processing of signals with completely correlated fluctuations leads to an energy gain caused by 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, energy gain as a result of joint signal processing (information fusion) is determined by the increase of total received signal energy. When a MSRS consists of wideband radars, small baselengths between spatially separated stations (compared with expected target range) may be used. Such MSRSs 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 for targets with approximately equal distances from radars. This is the more so, since resolved target flare spots have usually broad directivity pattern.

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 signal processing at each station and interstation processing.

From Eq. (2) we have optimum detection algorithm:

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[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.

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

Typical detection characteristics are shown in Fig. 2 for a MSRS with $m = 3$ the same radars as in Fig. 1. For 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.

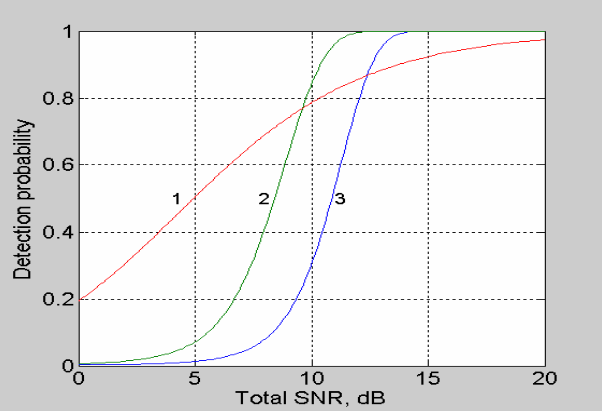

Fig. 2. Detection characteristics of the MSRS with $m = 3$ the same radars as in Fig. 1; the notation is the same as in Fig. 1; $M = 2$ echoes are processed at each radar; equal unknown target range profiles at each radar; $P_{fa}=10^{-3}$.

It is seen that UWB radars with short carrier-free pulses have better detection characteristics than UWB radars with carrier frequencies because of “coherent’’ signal processing of all 6 received signals. Energy gain caused by information fusion in the MSRS differs from 2.5…3.5 dB for the UWB radar with carrier frequency and the narrowband radar up to 5 dB for the UWB radar with short carrier-free pulses. Advantages over the narrowband radar begin from detection probability $P_d \approx 0.8$.

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 radar (or transmitting station). If range profiles are equal at the inputs of all the m receivers, the optimum detection algorithm takes the form:

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

When $m = 3$, and echoes of $M = 2$ repetition periods are processed at each radar, we have joint processing of 18 received signals. 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 to a 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.

When a target provides *different unknown range profiles relative to spatially separated stations*, and cooperative signal reception does not used, optimal signal processing is reduced to summation of energy estimates obtained at all stations:

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

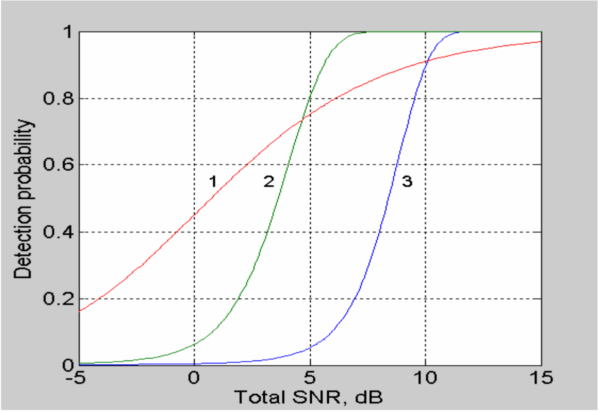

Fig. 3. Detection characteristics of the MSRS with $m = 3$ the same radars as in Fig. 1 and cooperative signal reception; the notation is as in Fig. 1; $M = 2$; equal unknown target range profiles at each radar; $P_{fa}=10^{-3}$.

It means that interstation processing becomes “incoherent”. This leads to energy losses. 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.

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 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 range profile received by the j-th station

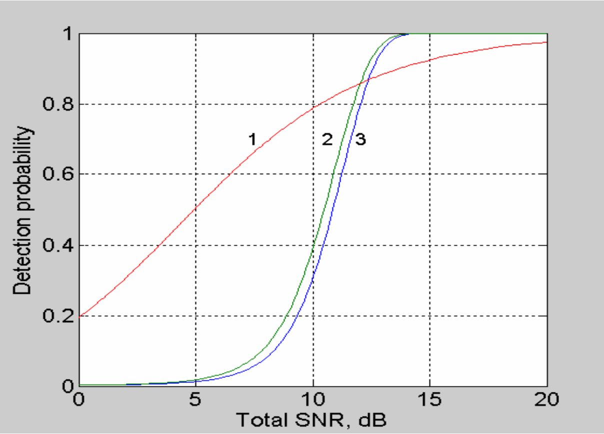

Fig. 4. Detection characteristics of the MSRS with *m* = 3 the same radars as in Fig. 1; the notation as in Fig. 1; *M* = 2 echoes are processed at each radar; different unknown target range profiles at each radar; $P_{fa}=10^{-3}$.

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* radars with equal technical characteristics the optimum detection algorithm takes the form:

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

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

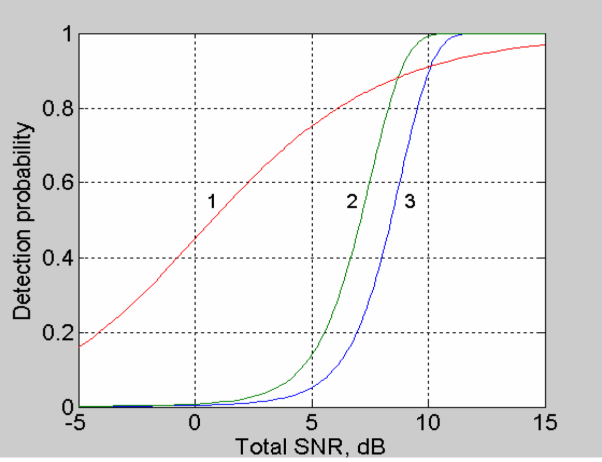

Fig. 5. Detection characteristics of the MSRS with *m* = 3 the same radars as in Fig. 1 and cooperative signal reception; the notation as in Fig. 1; *M* = 2 equal unknown target range profiles at each radar and *M* = 2 pairs of equal range profiles at *m* = 3 different radars; $P_{fa}=10^{-3}$.

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

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 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.

4 Conclusion

Detection characteristics of MSRSs consisting of UWB radars have been analyzed.

1. 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, and 2) radars using ultra-wideband pulses with carrier frequency (short pulses or pulses 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.
2. Detection characteristics are obtained 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.
3. 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 carrier-free UWB radars near to those of UWB radars with carrier frequencies.

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