Multisite Radar Systems with Information Fusion: 
A Technology of XXI Century

VICTOR S. CHERNYAK
Moscow State Aviation Institute (Technical University) 
31-1-12, Volgina ul., 117437 Moscow, 
RUSSIA

Abstract: In spite of impressive achievements in radar subsystem technology, traditional radars cannot in many cases meet modern (and long-term) high requirements to radar information. One promising way is to move from the individual radar to the Multisite Radar System (MSRS) that includes several spatially separated transmitting and receiving stations (or radars) coupled together for cooperative target observation [1]. In this paper, a wide definition of the MSRS is introduced. Main attention is paid to the most important advantages of MSRSs. We consider also main drawbacks of MSRSs. A list of modern applications of MSRSs is presented. In conclusion some prospects of MSRS development and applications are pointed out.

Key words: Radar Systems, Multistatic Radars, Multiradar Systems, Information Fusion

1 Introduction
In spite of impressive achievements in antennas, transmitters, receivers, processors, traditional radars cannot in many cases meet modern and long-term high requirements. One promising way is to move from individual radars to Multisite Radar Systems (MSRSs), which combine several spatially separated transmitting, and receiving stations (or radars) for cooperative target observation.

The fundamental idea behind MSRSs is to make more effective use of the information contained in the spatial characteristics of the electromagnetic field. The transition from individual radars to MSRSs is in agreement with the trend in modern engineering: to integrate individual technical means into systems where fundamental characteristics are enriched due to the interaction between system elements.

The modern development of MSRSs is based on the recent significant progress in adjacent technologies, especially in multichannel antennas with electronic scanning, high-speed digital processors and computers, transmission lines with high capacity and precise synchronisation systems.

2 Definition
A MSRS is a radar system including several spatially separated transmitting, receiving and (or) transmitting-receiving facilities where target information from all sensors is fused (jointly processed) [1]. This is a wide definition which covering both Multistatic Radars and Multiradar (Netted Radar) Systems. Thus, a MSRS has two principal distinctions: 1) several spatially separated stations and 2) fusion (joint processing) of target information. A typical structure of a MSRS is shown in Fig. 1. It may consist of several radars, transmitting and receiving stations connected by Data Transmission Lines (DTLs) with an Information Fusion Centre (IFC). MSRSs are classified in accordance with several essential attributes [1]: the type of targets of interest (active, passive and active-passive MSRSs), the degree of spatial coherence (spatially coherent, with short-term spatial coherence, spatially incoherent MSRSs), the information integration (fusion) level (with radio signal, video signal, plot and track integration levels), the degree of signal reception autonomy (with independent, cooperative and independent-cooperative signal reception), the station location and mobility (ground-based stationary and mobile, airborne, spaceborne, shipborne MSRSs) and the baselengths between stations (with “small” and “large” baselengths as compared with target ranges).

3 Main Advantages of MSRSs
Owing to information fusion from spatially separated stations, a MSRS presents significant advantages over both a monostatic radar and a collection of radars not integrated into a system. We note here only main advantages. The real possibilities of taking certain advantages depend on the type of a MSRS.

3.1 Increase of target detection range
Addition of transmitting or (and) receiving stations upgrades the total energy characteristics. However,
MSRs have some extra energy advantages. First is the cooperative signal reception when receiving stations can receive echoes from targets illuminated by any transmitting station.

Secondly, information fusion may lead to additional energy gain due to target fluctuation smoothing. Typical curves of energy gain for a system with one transmitting and \( m \) receiving stations, false alarm and detection probabilities \( P_a = 10^{-4}, P_d = 0.9, 0.99 \) (curve 2 and 3) as compared to coherent summation for any \( P_d \) (curve 1) are shown in Fig. 2. Fig. 3 illustrates increase of target detection range.

\[
\sigma_b(\beta=180^\circ) = 4\pi S_b^2/\lambda^2
\]  

(1)

where \( \lambda \) is the wavelength and \( S_b \) is the geometric area of the target silhouette. If \( \varepsilon \) is small, \( \sigma_b \gg S_b \).

### 3.2 High accuracy of target localisation

As a rule, distant target localisation by a usual radar is much less accurate in cross-range direction than in down-range one. Fig. 4 shows sections of two error ellipsoids obtained as a result of target position measurement by each of the two radars. The intersection of these ellipsoids may be considered as a resultant error ellipsoid after information fusion. A noticeable gain in the target position estimation accuracy (due to range measurements) can be seen. It may be treated as the increase of the angle coordinate estimate accuracy. Angle r.m.s. equivalent error, \( \sigma(\theta) \), in a pair of radars can be approximately expressed as follows:

\[
\sigma(\theta) = \sigma(R)/\sqrt{2}/L \sin \theta = \sigma(R)/\sqrt{2}/L_{\text{eff}}
\]  

(2)

Here \( \sigma(R) \) is the r.m.s. error of statistically independent range measurements of each radar; \( L \) is the baselength; \( L_{\text{eff}} \) is the effective baselength. Equation (2) has been derived under “small baselength” condition (target range \( R \gg L_{\text{eff}} \)) but it may be used even when \( R > (2\ldots3) L_{\text{eff}} \).

**Example 3.1.** Let \( \sigma(R) = 5 \text{ m}, L_{\text{eff}} = 30 \text{ km} \). Then (2) yields \( \sigma(\theta) = 0.8' \).

It can be seen that if signal bandwidths and effective baselengths are sufficiently large, \( \sigma(\theta) \) may be much less than that of a usual bearing measurement by a monostatic radar. Thanks to this feature, large and expensive antennas may sometimes be replaced by small, weakly directional antennas without accuracy loss of target localisation.

### 3.3 Estimation of target velocity and acceleration vectors by the Doppler method

Doppler Frequency (DF) measurements of target echoes at several spatially separated stations allow one to estimate the velocity vector of a target. This may be of great importance for accurate target tracking, especially along the manoeuvre portions of target paths etc. In a simplest system with two radars, baselength \( L \) and independent signal reception the DFs that can be measured are:

\[ F_{D1} = 2V_t/\lambda \text{ and } F_{D2} = 2V_t/\lambda \]

where \( V_{t1}, V_{t2} \) are the target radial velocities relative to radar 1 and radar 2, respectively. If \( \mathbf{V} \) is the target velocity vector in the plane of Fig. 5, the r.m.s. errors of the radial, \( \sigma(V_R) \), and tangential, \( \sigma(V_T) \), velocity estimation are as follows [\( \sigma(F) \) is the r.m.s. error of each radar DF measurements]:

\[
\sigma(V_R) = \left(\lambda/2\sqrt{2}\cos(\beta/2)\right)\sigma(F) = \left(\lambda/2\sqrt{2}\right)\sigma(F);
\]

(3)

\[
\sigma(V_T) = \left(\lambda/2\sqrt{2}\sin(\beta/2)\right)\sigma(F) = \left(\lambda/2\sqrt{2}\right)(R/L_{\text{eff}})\sigma(F).
\]

The approximate equalities in (3) are valid under the condition \( R/L_{\text{eff}} \gg 1 \) when \( \cos(\beta/2) = 1, \sin(\beta/2) = (\beta/2) = L_{\text{eff}}/2R \). It is seen that \( \sigma(V_T) \) is greater by \( \cotan(\beta/2) = 2R/L_{\text{eff}} \) than \( \sigma(V_R) \) for the same \( \sigma(F) \).

**Example 3.2.** Let DFs be measured with the help of a coherent pair of signal pulses transmitted with the time interval \( T = 5 \text{ ms} \). Then
\[ \sigma(F) = \sigma(\phi) \sqrt{2} / 2 \pi T \]  \hspace{1cm} (4)

where \( \sigma(\phi) \) is the r.m.s. error of each pulse phase measurement. Let \( \sigma(\phi) = 7.2^\circ = 0.02\,\pi \). For the same pair of radars as in Example 3.1 with \( L_{\text{eff}} = 30 \) km. and \( \lambda = 0.1 \) m we have [according to (3) and (4)]: \( \sigma(F) = 2.828 \, C_2, \sigma(V_R) = 0.2 \) m/s. For the target range \( R = 300 \) km \( \sigma(V_T) = 4 \) m/s. Though \( \sigma(V_T) >> \sigma(V_R) \), such an error is by several orders smaller than can be achieved by antenna angular measurements for the same time interval \( T = 5 \) ms.

The target acceleration vector can be obtained by estimating the speed of DF variations or by differentiating the velocity vector components.

### 3.4 Capability to measure three coordinates and velocity vector of radiation sources

Unlike both monostatic and bistatic radars that can measure only Directions Of signal Arrival (DOAs) in passive mode, MSRSs can obtain all the three coordinates. This may be achieved by triangulation, or hyperbolic methods, or their combination. The triangulation determines the position of a radiation source in 3D space as the intersection point of DOAs from spatially separated stations. The hyperbolic method determines the source position as the intersection point of hyperboloids of revolution, having their foci at each pair of stations. A fixed Time Difference Of signal Arrival (TDOA) at a pair of stations determines the hyperboloid of revolution on which surface the source must lie. A TDOA is estimated by the signal delay in one station, which is necessary to maximise the mutual correlation of signals received by the two stations. Real source localisation errors depend on the accuracy of DOA and TDOA measurement in triangulation and hyperbolic systems, respectively, and on the system geometry. When \( R >> L_{\text{eff}} \), linear cross-range errors of both methods are proportional to range, while down-range errors are proportional to squared range. Under this condition, a TDOA measurement with the r.m.s. error \( \sigma(\delta t) \) (for the hyperbolic method) is approximately equivalent to a bearing measurement with the r.m.s. error \( c \) (the light velocity)

\[ \sigma(\theta)_{eq} = c \sigma(\delta t) / L_{\text{eff}} = \sigma(\Delta R) / L_{\text{eff}} \]  \hspace{1cm} (5)

**Example 3.3.** A pair of stations with the \( L_{\text{eff}} = 30 \) km and \( \sigma(\delta t) = 33 \) ns \( (\sigma(\Delta R) = 10 \) m, i.e. signal bandwidth \( \Delta f_s = 5-10 \) MHz) is approximately equivalent to a direction finder placed in the midpoint of the baseline with the bearing accuracy \( \sigma(\theta)_{eq} = 3.3 \times 10^{-4} \) rad \( \approx 1.2^\circ \). It is difficult to achieve such a small error by a monostatic radar with a usual antenna size.

The DF measurements of the mutual correlation function of signals received by a pair of stations makes it available to estimate the source radial velocity difference relative to these stations. A MSRS containing four or more stations can obtain the source velocity vector. The MSRS’s capability to determine three space coordinates and velocity vector of a radiation source is an important feature for tracking jammers, when they prevent tracking targets. The passive mode of MSRSs may be used for reconnaissance of hostile radars (as a means of ESM), in ATC systems with SSRs etc.

### 3.5 Increase of resolution capability

It is seen from Fig. 6 that two targets fallen into one resolution cell in range and angle are not resolved by radar 1. If, as is normal the practice, range resolution of a radar is much better than cross-range resolution, the angle difference between targets (relative to radar 1) may be enough to resolve targets in range by radar 2. This effect may be treated as the capability of MSRSs to resolve targets in angle within main antenna beams. The equivalent angular resolution capability of a system of two radars may be obtained from the range resolution capability of each radar \( \Delta R = c/2f_s \) where \( \Delta f_s \) is the signal bandwidth. When \( R >> L_{\text{eff}} \),

\[ \delta \theta = \delta R / L_{\text{eff}} = c / 2L_{\text{eff}} \Delta f_s \]  \hspace{1cm} (6)

The value \( \delta \theta \) in (6) may be treated as the beamwidth of a “Resultant Directivity Pattern (RDP)” of a pair of radars. When the product \( L_{\text{eff}} \Delta f_s \) is large enough, the beamwidth of a RDP is much less than that of a usual antenna.

**Example 3.4.** Let again \( L_{\text{eff}} = 30 \) km and \( \Delta f_s = 10 \) MHz. Then (6) yields \( \delta \theta = 5 \times 10^{-3} \) rad \( \approx 1.7^\circ \). Apparently, this is very high angular resolution.

### 3.6 Increase of jamming resistance

All ECCM methods used in monostatic radars can be utilised in MSRS as well. Besides, MSRSs have some extra important capabilities.

It is difficult to provide highly directional jamming against several stations of a MSRS with sufficient spatial separation. If a MSRS contains transmitting stations operating in several frequency ranges, and
cooperative signal reception is used, such a MSRS is virtually immune to narrowband intensive spot-noise jamming. Forced spreading of jammer power over a wide solid angle and over a wide frequency range results in lowering jamming power density incident upon each receiving station within its frequency band. Such MSRSs are much less vulnerable to retrodirective deception (target echo-like) and repetitive pulse jamming, especially if distinctions in Times Of Arrival (TOAs) of target echoes and interferences are taken into account.

A spatially coherent MSRS creates a focal spot of a very small angular size. It means that a jammer and a concealed target cannot be together within this focal spot for a long time, except the case of self-screening when the jammer is onboard the target. Spatially coherent MSRSs and (practically more important) MSRSs with short-term spatial coherence have a unique capability to detect targets in the presence of intensive mainlobe jamming. The mainlobe jamming cancellation is carried out with the help of special Adaptive Mainlobe Jamming Cancellation Algorithms (AMJCAs). A simple example shows the performance of one of AMJCAs.

**Example 3.5.** The simulated system is depicted in Fig. 7. An aircraft moves from the range \( R(0) = 300 \text{ km} \) at a constant height with the constant velocity \( V = 0.8 \text{ km/s} \). The baselength \( L = L_{\text{eff}} \) has been chosen so, that echo fluctuations are mutually independent at the receivers. At \( t = 0 \) the aircraft has a jammer onboard (self-screening situation). Then the jammer leaves the aircraft and moves with the same velocity as the aircraft but in slightly different direction, so that the cross-range distance between the aircraft and the jammer increases by approximately 1.5 m per a second. Such a model is used to reveal the algorithm performance in the most difficult cases where a jammer and a target coincide in space or are in close proximity to each other. Beamwidths of both stations are \( 1^\circ \) in azimuth and elevation, that is approximately 5.2 km at the range 300 km, so that antennas cannot resolve the jammer and the aircraft. The output of the AMJCA undergoes the usual processing. Typical plots of the output of the envelope detector are shown in Fig. 8. When the AMJCA is switched off, the target echo is perfectly masked by jamming. When the AMJCA is switched on, the target echo is detected with confidence. The input and output signal-to-interference-plus-noise ratios (SINRs) are approximately \(-2 \text{ dB}\) and \(+23 \text{ dB}\), respectively. The input SINR at each receiver and the SINR at the output of the AMJCA before envelope detection are shown in Fig. 9. It is seen that the aircraft can be surely detected even when the jammer is onboard, i.e. when the jammer and the aircraft coincide in space. Thanks to the echo fluctuation spatial independence, jamming coherent subtraction is accompanied by incoherent echo summation. Thus, multisite radar systems can solve one of the most difficult radar problems: target detection under the intensive mainlobe jamming.

**3.7 Increase of clutter resistance**

When transmitting and receiving stations are spatially separated in a MSRS, intersection volume of their mainbeams can be much less, than mainbeam volume of a corresponding monostatic radar. It results in essential reduction of intensity of clutter at the inputs of receivers under typical conditions of chaff. Besides, in such cases clutter returns from near large objects are less intensive than with a monostatic radar, since these objects cannot be at short ranges from both transmitting and receiving stations. Highly directional reflectors with a large RCS, such as trihedrals, are ineffective, because they concentrate the reflected energy towards transmitters.

If a MSRS consists of several spatially separated radars operating in different frequency ranges, resonant chaff matched to one frequency range cannot usually conceal targets for the MSRS.

Unfortunately, signals scattered by volumetric clutter (e.g., chaff “clouds”) are, as a rule, mutually
uncorrelated at the inputs of spatially separated stations. Therefore, coherent subtraction (cancellation) of clutter signals received by different stations is impossible. Only target echo integration in a background of spatially uncorrelated clutter signals is possible for enhancing detection characteristics.

All Moving Target Indication (MTI) techniques used in monostatic radars can be utilised in MSRSs. Furthermore, MSRSs are free of limitations inherent in monostatic radars caused by zero or blind radial velocities of a moving target because target radial velocities are different relative to different stations.

A more flexible choice of transmitting waveforms can be made with MSRSs. In particular, pulse signals with high PRF for effective clutter cancellation can be employed. Possible range ambiguities can be resolved, for example, by triangulation.

Among other important advantages of MSRSs, it should be mentioned also increase of handling capacity in multitarget environment, increase of signal information body for target recognition, increase of survivability and reliability (“graceful degradation” feature).

4 Main Drawbacks of MSRSs
Main drawbacks are, as a rule, additional difficulties which one has to overcome when creating a MSRS. They may be considered as the “price” of the advantages of MSRSs.

• Necessity of centralised control
Depending on the type of a MSRS this control can be reduced to target distribution among several groups of radars or can solve more complex tasks: coordinated scanning of space (in particular, “pulse chasing”), choice of operational frequencies, waveforms for different transmitters and receivers, processing algorithms etc.

• Necessity of data transmission lines
Each MSRS must contain either analogue or digital Data Transmission Lines (DTLs) for signal or data transmission from spatially separated stations to an Information Fusion Centre (IFC). They are used for command and control information transmission too.

• Additional requirements to synchronisation, phasing of stations, transmission of reference frequencies and signals
Some kind of synchronisation between different stations and IFC is necessary for information fusion. Specific requirements depend on the type of a MSRS. When cooperative signal reception is used, then the frequency and the signal waveform emitted by any transmitting station (or radar) must be known at receiving stations (or at other radars). For coherent signal processing at each receiver (MTI systems, Doppler measurements), a common reference frequency is necessary at each station. In spatially coherent MSRSs additional phasing of stations (phase synchronisation) is required. All these problems have been solved in operational systems.

• Increased requirements to signal and data processors and computer systems
In fact, this is a consequence of one of principal advantages of MSRSs: a significant increase of the total information body from a target. However, there are certain special procedures increasing computational burden. These are: 1) coordinate conversion of radar data from a local coordinate system connected with each station into a common coordinate system of a MSRS, and 2) interstation data association between measurements (plots, tracks) obtained by different stations, on the one hand, and targets, on the other. Besides, most geometrical relationships and tracking algorithms are more complicated than for monostatic radars. The state-of-the-art of signal processor technology and computer engineering is quite sufficient to meet all actual requirements.

• Necessity of accurate station positioning and mutual alignment
Errors of station position determination and of local coordinate axes orientation influence directly on the accuracy of output information. Positions of both stationary and mobile stations can be determined with sufficient accuracy by using the GPS “NAVSTAR” (USA) and “GLONASS” (Russia).

• Need for lines-of-sight (not necessary straight) between stations and targets
Information fusion from targets that are not visible to at least several stations is impossible. This may be an important constraint for low-level targets observation by ground-based MSRSs.

• MSRSs are usually more complex and expensive than monostatic radars
However, comparison in complexity and cost is correct if capabilities and performance characteristics of compared systems are equal. Certain capabilities of MSRSs are absent in monostatic radars, while realisation of some other characteristics requires a drastic increase of complexity and cost (for example, employment of phased antenna arrays of enormous size). In some cases a MSRS containing simple stations of the same type is less expensive than a monostatic radar with similar technical characteristics. Of course, deployment of MSRSs is reasonable if usual simple not expensive monostatic radars cannot meet imposed requirements.

In many cases significant benefits can be obtained at the low cost when a MSRS is created by
integrating operational radars or by adding remote receiving stations to operational radars.

5. Main Modern Applications

5.1 Military
- Interference resistant Air Defence (AD) and Ballistic Missile Defence (BMD) systems with high accuracy of target coordinate measurement and tracking, high survivability and reliability (including systems for Stealth target detection) (e.g., [1-3]).
- Passive systems for jammer localisation and tracking, hostile radar localisation (e.g., [1, 4]).
- Radar systems consisting of surface-wave and sky-wave Over-The-Horizon (OTH) radars for target detection at long distances with improved target coordinate measurement accuracy (e.g., [1,5]).
- High precision measurement radar systems for test ranges (e.g., [1,6]).
- As a part of Multisite Information Systems (MISs) containing sensors of dissimilar physical nature (e.g., [7,8]).

5.2 Civil
- Automated Air Traffic Control (ATC) systems including en-route and near airdrome systems with primary and secondary, active and passive radars (e.g., [1, 9]).
- Active and passive MSRSs for surface movement control on airport manoeuvring areas, take-off and landing runways (e.g., [1,10]).

6. Conclusion
- Multisite Radar Systems have many important advantages in comparison with monostatic or bistatic radars and even with collections of radars not integrated into MSRSs. In many cases where stringent requirements are imposed for radar information, interference resistance, reliability and survivability, MSRSs can be a good, cost-effective solution.
- Theoretical fundamentals of MSRSs have, on the whole, been developed (e.g., [1]). Principal theoretical results are based on the general statistical detection theory, estimation theory and filtration theory. At the same time, there are many not fully solved important problems. Among them are the problems of target detection and parameter estimation in multi-target environment, parameter estimation and tracking of extended targets, target imaging, effective control and management of power and information resources of MSRSs and some others.
- Most MSRSs have been developed and are now being developed for military applications. However, during the last years one can observe a trend to more intensive development of civil MSRSs and MSRSs for dual applications.
- Recent practical applications of MSRSs show that in certain cases a MSRS, being superior in performance, turns out to be cheaper and simpler than a monostatic radar designed for the same purposes.

   Multisite Radar Systems have good prospects for both military and civil applications. This is a technology for the XXI century. An important trend is to integrate MSRSs into more general Multisite Information Systems (MISs) with sensors of dissimilar physical nature.

References