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<table>
<thead>
<tr>
<th>CONTENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mathematics</strong></td>
</tr>
<tr>
<td><em>Tsetska Rashkova</em></td>
</tr>
<tr>
<td>Grassmann algebra’s PI-properties in matrix algebras with Grassmann entries</td>
</tr>
<tr>
<td><em>Antoaneta Mihova</em></td>
</tr>
<tr>
<td>A comparison of two methods for calculation with Grassmann numbers</td>
</tr>
<tr>
<td><em>Mihail Kirilov</em></td>
</tr>
<tr>
<td>δ - Characteristic sets for finite state acceptor</td>
</tr>
<tr>
<td><em>Mihail Kirilov</em></td>
</tr>
<tr>
<td>λ - Characteristic sets for finite Mealy automaton</td>
</tr>
<tr>
<td><em>Veselina Evtimova</em></td>
</tr>
<tr>
<td>Research on the utilization of transport vehicles in an emergency medical care center</td>
</tr>
<tr>
<td><em>Valerij Djurov, Milena Kostova, Ivan Georgiev</em></td>
</tr>
<tr>
<td>A mathematical model system for radiolocational image reconstruction of dynamic object with low radiolocational visibility</td>
</tr>
<tr>
<td><strong>Informatics</strong></td>
</tr>
<tr>
<td><em>Tzvetomir Vassilev</em></td>
</tr>
<tr>
<td>Soft shadows for GPU based ray-tracing</td>
</tr>
<tr>
<td><em>Rumen Rusev, Ana Kaneva</em></td>
</tr>
<tr>
<td>Software module for spectral analysis of audio signals</td>
</tr>
<tr>
<td><em>Galina Atanasova, Plamenka Hristova, Katalina Grigorova</em></td>
</tr>
<tr>
<td>An approach to flow charts comparing</td>
</tr>
<tr>
<td><em>Valentin Velikov</em></td>
</tr>
<tr>
<td>Computer viruses and effectively protection of the home users</td>
</tr>
<tr>
<td><em>Georgi Krashev</em></td>
</tr>
<tr>
<td>Nonhierarchical method for clustering</td>
</tr>
<tr>
<td><em>Valentina Voinohovska, Svetlozar Tsankov</em></td>
</tr>
<tr>
<td>Corporate presence web site for dental clinic</td>
</tr>
<tr>
<td><em>Metodi Dimitrov</em></td>
</tr>
<tr>
<td>Global repository for sequences of robots instructions</td>
</tr>
<tr>
<td><em>Svetlozar Tsankov, Valentina Voinohovska</em></td>
</tr>
<tr>
<td>(X)HTML E-handbook in the discipline “Multimedia systems and technologies” for teaching and learning purposes</td>
</tr>
<tr>
<td><strong>Physics</strong></td>
</tr>
<tr>
<td><em>Galina Krumova</em></td>
</tr>
<tr>
<td>Momentum distributions of medium and heavy neutron-rich nuclei</td>
</tr>
<tr>
<td><em>Galina Krumova</em></td>
</tr>
<tr>
<td>Deformation effects on density and momentum distributions of 98kr nucleus</td>
</tr>
</tbody>
</table>
A MATHEMATICAL MODEL SYSTEM FOR RADIOLOCATIONAL IMAGE RECONSTRUCTION OF DYNAMIC OBJECT WITH LOW RADIOLOCATIONAL VISIBILITY

Valerij Djurov, Milena Kostova, Ivan Georgiev

Angel Kanchev University of Ruse

Abstract: A mathematical model of a system for reconstruction of aircraft radiolocation image, constructed using modern technology for radiolocation visibility reduction, so called metamaterial, is offered. Linear orthogonal frequency drilling signals and principles of the inverse synthetic aperture radar are used. Images of aircraft F117 are received by software implementation of the mathematic model with horizontal and vertical polarization of the drilling signal. The guidelines for the created model application are indicated for increasing the quality when radiolocation images are restored.

Keywords: Mathematical Model, Orthogonal Signals, Fourier Transformation, Inverse Synthetic Aperture Radar.

INTRODUCTION

One of the main objectives of radiolocation recognition is to determine the type of the observed object. This can be achieved by radiolocation image reconstruction (RIR) of the observed aircraft. The variety of flying objects and construct decisions for reducing their radiolocation visibility poses challenges to professionals working in radio intelligence. These challenges are greater at objects with low radiolocation visibility because of the use of composite materials and technologies, causing new physical properties and phenomena [11]. Modern technology for reducing the radiolocation visibility is so called metamaterial [3]. This is a matter with certain microscopic structures whereby some specific properties such as negative refraction coefficient, reverse Doppler effect, Cherenkov effect and others are achieved. A mathematical model of approach for RIR of objects filled with metamaterial, is presented. The approach is based on parallel processing of radiolocation information by object, using drilling orthogonal linear frequency modulated signals (OLFMS).

MATHEMATICAL MODEL OF A SYSTEM FOR PARALLEL PROCESSING OF RADIOLOCATIONAL IMAGE USING DRILLING ORTHOGONAL LINEAR FREQUENCY MODULATED SIGNALS

Signals used in radiolocation depend on the technical, technological and structural characteristics of the radiolocation systems. The choice of them is related to the purpose of the radar observation and the specificity of the observed dynamic object [4,10]. The use of complex signals is dictated by the development of modern technologies (Stealth technologies, plasma cover, metamatter), aiming to reduce the radiolocation visibility of dynamic objects.

Multi-frequency signals as a complex signals with wide base can be also used for obtaining images from objects with low effective reflective surface [2,5,6,9,10]. Radiolocation images of dynamic objects can be realized using: linear frequency modulated signal, linear frequency modulated signal with a step-change of carrier frequency, discrete set of components of the carrier frequency changing by a certain law [1,2].

Tests had been developed for receiving RIR of objects surrounded by Stealth technology [4,7] using drilling linear frequency modulated signals, which don’t give sufficiently good results at objects with metamatter. This determines the necessity of
applying different approach with using OLFMS. Modern communication systems use “orthogonal signals” OFDM (Orthogonal Frequency Division Multiplexing) [1,9].

Mathematical models of two parallel working systems with OLFMS appliance, respectively vertical polarized with index \((V)\) and horizontal polarized with index \((H)\) using the theory of inverse aperture synthesis are presented. The two algorithms are combined in one mathematical model.

The object is presented in discrete form as a set of discrete point emitters \((m, n)\), situated in a rectangular Euclid grid \(O'XY\) standing at a distance \(\Delta X, \Delta Y\), respectively at axes \(O'X\) and \(O'Y\). It is accepted that the object’s geometrical center matches with the beginning of the coordinate system \(O\) [4]. The coordinates of every \((m, n)\)-th pointer emitter \((m = 1, M; n = 1, N)\) in the coordinate system \(O'XY\) have the following form:

\[
\begin{align*}
X_{mn} &= n \Delta X \\
Y_{mn} &= m \Delta Y
\end{align*}
\]

The matrices \([X], [Y]\) are formed with scale \((M \times N)\) and with elements - the values \(X_{mn}, Y_{mn}\). The coordinates of every simple reflector against the coordinate system \(Oxy\) are changing during the process of synthesizing the aperture. The law of change is given with a matrix equation [7]:

\[
\begin{bmatrix}
x \\
y
\end{bmatrix} = \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} - T_p \left( \frac{N_p V^{(H)}}{2} - p \right) V_x V_y + A_p \begin{bmatrix} X \\ Y \end{bmatrix},
\]

where \(p = 1, N_p V^{(H)}\) is the number of the current drilling impulse for vertical and horizontal polarized frequency, \(N_p V^{(H)}\) is the total impulse number in the sequence for every vertical and horizontal polarized frequency; \(x_0, y_0\) are coordinates of \(p\), \(O'\) in the coordinate system \(Oxy\) at moment \(p = \frac{N_p V^{(H)}}{2}\); \(T_p V^{(H)}\) is an impulse repetition period for drilling orthogonal signal; \(V_x, V_y\) are speed vector components at corresponding axis; \(A_p\) - matrix of transformation.

The distance to each point \((m, n)\) of the object space, for every \(p\)-th impulse from the sequence of drilling impulses is determined by the equation:

\[
R_{mn}(p) = \sqrt{x_m^2(p) + y_m^2(p)}, \text{ where } p = 1, N_p V^{(H)} [4].
\]

Analytical record of the sequence of pulses in the drilling complex type of vertically and horizontally polarized signal is represented by the equation:

\[
S^{(H)}(t) = A_s V^{(H)} \exp[j(\omega V^{(H)}t \pm \mu V^{(H)} t^2)],
\]

where \(A_s V^{(H)}\) is the amplitude of the emitted orthogonal signal, \(\omega V^{(H)} = 2\pi f^{(H)}\) is the circular frequency, \(f^{(H)}\) - the main carrying impulse frequency for the corresponding polarization, \(t\) - the current time, \(\mu V^{(H)} = \frac{2\pi \Delta F V^{(H)}}{T V^{(H)}}\) - the variation rate of frequency.
modulation, \( \Delta F^{(H)} \) - the frequency deviation, \( T^{(H)} \) - the pulse duration at corresponding polarization.

The number of needed impulses \( N_p^{(H)} \) for realization of resolution at azimuth \( \Delta L \) is given using the formula \[4,7\]:

\[
N_p^{(H)} = \frac{0.5 \lambda R}{\Delta L T^{(H)} p V \sin(\beta + \varphi)},
\]

where \( \lambda \) is wavelength, \( N_p^{(H)} \) - drilling impulse repetition period for the corresponding polarization, \( R \) - traverse distance to the object's mass center at a moment \( p = \frac{N_p^{(H)}}{2} \).

Each of the point emitters from object space reflects radiation pulse using the law:

\[
s_{mn}^{(H)} = A_{mn}^{(H)} \exp[j(\omega^{(H)}(t - \tau_{mn}^{(H)}) \pm \mu^{(H)}(t - \tau_{mn}^{(H)})^2)],
\]

where \( A_{mn}^{(H)} \) is amplitude of the reflected signal at corresponding polarization by \((m,n)\)-th simple reflector; \( \tau_{mn}^{(H)}(p) = \frac{2R_{mn}^{(H)}(p)}{c} \) - delay time of the reflected signal by the \((m,n)\)-th simple reflector at vertical and horizontal polarized signal; \( c = 3.10^8 [m/s] \) - speed of electromagnetic energy.

The duration of the reflected impulse for orthogonal signals in general case can be described by the expression:

\[(9)\]

\[
T_p^{(H)} = T^{(H)} + (\tau_{\text{max}}^{(H)} - \tau_{\text{min}}^{(H)})
\]

By putting \( T^{(H)} = k\Delta T^{(H)} \) and \( \tau_{\text{max}}^{(H)} - \tau_{\text{min}}^{(H)} = l\Delta T^{(H)} \), where \( k = 1, N_k^{(H)} \), \( l = 1, L^{(H)} \), impulse time discretization is realized . Equation (9) has the following look:

\[
(10)\]

\[
T_p^{(H)} = k\Delta T^{(H)} + l\Delta T^{(H)}
\]

The current discrete time \( t \), for which the reflected impulse is elapsing, is given with the expression:

\[
(11)\]

\[
t = \tau_{\text{min}}^{(H)} + k\Delta T^{(H)} + l\Delta T^{(H)}
\]

The sum of all complex values of the reflected signals by all point emitters from every \( p \)-th impulse and every \( k \)-th time discrete for orthogonal signals is given with the expression:

\[
(12)\]

\[
\sum_{m=1}^{M} \sum_{n=1}^{N} \hat{S}_{mn}^{(H)}
\]

A \( S_{k}^{(H)}(k, p) \) matrix is formed with elements the partial sums \( \hat{S}_{kp}^{(H)} \), where \( k = 1, N_k^{(H)} \), \( p = 1, N_p^{(H)} \). The matrix is the discrete record of the complex trajectory signal, reflected by the object for the whole period of aperture synthesizing using drilling orthogonal signals:

\[
(13)\]

\[
S_{k}^{(H)}(k, p) = \sum_{m=1}^{M} \sum_{n=1}^{N} A_{mn}^{(H)} \exp[j(\omega^{(H)}(t - \tau_{mn}^{(H)}(p)) \pm \mu^{(H)}(t - \tau_{mn}^{(H)}(p))^2)]
\]

The discrete values of the complex trajectory signal form the matrix \( S_{k}^{(H)}(\bar{k}, p) \).
(14) \[ S^{v(H)}(\bar{k}, p) = \sum_{m=1}^{M} \sum_{n=1}^{N} A_{mn}^{v(H)} \text{rect}[t - \tau_{mn}^{v(H)}(p)] \times B^{v(H)}, \text{ at} \]

(15) \[ B^{v(H)} = \exp\{j[\omega^{v(H)}(\tau_{\min}^{v(H)}(p) + \bar{k}\Delta T^{v(H)} - \tau_{mn}^{v(H)}(p)) \pm \mu^{v(H)}(\tau_{\min}^{v(H)}(p) + \bar{k}\Delta T^{v(H)} - \tau_{mn}^{v(H)}(p))^2]\} \]

where \( \bar{k} = 1, N_{k}^{v(H)} + L^{v(H)}(p); \ p = 1, N_{p}^{v(H)}, \)

(16) \[ \text{rect}[t - \tau_{mn}^{v(H)}] = \begin{cases} 1, & 0 \leq t - \tau_{mn}^{v(H)} \leq T^{v(H)} \\ 0, & t - \tau_{mn}^{v(H)} < 0 \\ 0, & t - \tau_{mn}^{v(H)} > T^{v(H)} \end{cases} \]

The rectangular function limits the time duration for each reflected impulse, so that it does not exceed the duration of the impulse itself. For each \( p \)-th reflected impulse, multiplication of the complex matrix elements \( S^{v(H)}(\bar{k}, p) \) by complex-conjugate transmitted signal is accomplished.

(17) \[ S^{v(H)}(k, p) = S^{v(H)}(\bar{k}, p) \exp[-j(\omega^{v(H)}t \pm \mu^{v(H)}t^2)], \]

where \( t = k\Delta T^{v(H)}; k = 1, N_{k}^{v(H)} \); \( \bar{k} = \left( \frac{L^{v(H)}}{2} + 1 \right), (N_{k}^{v(H)} + \frac{L^{v(H)}}{2}), \ p = 1, N_{p}^{v(H)} \)

After proper transforming equation (17) has the following look:

(18) \[ S^{v(H)}(k, p) = \sum_{m=1}^{M} \sum_{n=1}^{N} A_{mn}^{v(H)} \text{rect}[k\Delta T^{v(H)} - \tau_{mn}^{v(H)}(p)] \times C^{v(H)} \]

where

(19) \[ C^{v(H)} = \exp\{j\left[\omega^{v(H)}(\tau_{\min}^{v(H)}(p) - \tau_{mn}^{v(H)}(p)) \pm \mu^{v(H)}(\tau_{mn}^{v(H)}(p) - \tau_{\min}^{v(H)}(p))^2 + 2\mu^{v(H)}k\Delta T^{v(H)}(\tau_{mn}^{v(H)}(p) - \tau_{\min}^{v(H)}(p))\right]\} \]

By applying the discrete Fourier transform to the orthogonal sum of harmonic signals \( S^{v(H)}(k) \) it is possible to achieve a result in the frequency area, reflective and dependent by the differences in the time delay of signals from different point emitters. This transformation realizes distance compression of the complex trajectory signal and obtains information about the spacious situation of the point emitters in different remoteness bands towards the radiolocation station.

Towards each of the matrix columns of the demodulated complex trajectory signal \( S^{v(H)}(k, p) \) is applied discrete Fourier Transform [6] which has the following look:

(20) \[ S^{v(H)}(k, p) = \frac{N_{k}^{v(H)}}{\sum_{q=1}^{N_{k}^{v(H)}} S^{v(H)}(q, p) \exp[-j2\pi(q-1)(k-1)]}, \]

where \( k \) is the element number bypassing the rows for first strobe, \( k = 1, N_{k}^{v(H)} \), \( p = 1, N_{p}^{v(H)} \).

An image reconstruction is completed by Discrete Fourier Transform, applied towards the rows of the matrix \( S^{v(H)}(k, p) \) (component compression of the signal path in azimuth).
\[
S_{V(H)}^{(k,p)} = \sum_{r=1}^{N_p} S_{V(H)}^{(k,r)} \exp \left[ -j2\pi(r-1)(p-1) \right],
\]

where \( k = 1, N_k \), \( p = 1, N_p \), \( q \) and \( r \) are sum indices with corresponding values \( q = 1, N_q \), \( r = 1, N_r \).

Based on the developed mathematical models, software applications are created in Matlab environment \([8]\). Standard and reconstructed images of a F117 object, at vertical and horizontal drilling polarized signals are presented on Fig.1. The results show the correctness of the developed models. It gives the opportunity on parallel work of the two algorithms in system for restitution of RIR, information for the observed radiolocation object to be supplemented aiming to raise the quality of the reconstructed image of the object covered with metamaterial and Stealth technology.

**Fig. 1.** Standard image (a), reconstructed image at vertical polarization (b) and reconstructed image at horizontal polarization (c) of F117 object.

**REFERENCES**


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МАТЕМАТИЧЕСКИ МОДЕЛ НА СИСТЕМА ЗА ВЪЗСТАНОВЯВАНЕ РАДИОЛОКАЦИОННО ИЗОБРАЖЕНИЕ НА ДИНАМИЧЕН ОБЕКТ С НИСКА РАДИОЛОКАЦИОННА ЗАБЕЛЕЖИМОСТ

Валерий Джуров, Милена Костова, Иван Георгиев

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Резюме: Представлен е математически модел на система за възстановяване на радиолокационно изображение на самолет, конструиран чрез съвременна технология за намаляване на радиолокационната забележимост - т. н. метаматерия. Използвани са линейно честотни ортогонални сондиращи сигнали и принципите на обратния апертурен синтез. Получени са изображения на самолет F117 чрез софтуерна реализация на математически модел при хоризонтална и вертикална поляризация на сондиращия сигнал. Посточени са насоките за приложение на създавания модел за повишаване качеството при възстановяване на радиолокационни изображения.

Ключови думи: Математически модел, Ортогонални сигнали, Преобразуване на Фурие, Обратен апертурен синтез, Метаматерия, Радиолокационно изображение.