A model for tracking process of the integrated radar systems under working conditions with maneuvering targets

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Abstract. The article presents the organization of the process of simulation modeling of the functioning the integrated radar systems in the detection, measurement and tracking modes. The aim of the work is to develop a simulation model that allows to evaluate the effectiveness of the algorithms of radar tracking of targets. The description of analytical models and their interaction and simulation results are presented. The construction of the model is implemented in the software MathCad 15.0.

1. Introduction

The methods of calculating the flight paths of aircraft have been gradually and steadily improved; while from time to time new challenges appear with the development of the theory of radar detection and tracking of targets. In other words, in other words, there is a tendency to increase the information content of observations made with the help of radar stations. One of the challenges, that is relevant for integrated radar systems (IRS) of various classes, is the issue of tracking maneuvering and complex targets. These target classes represent the main sources of uncertainty in the theory of digital processing of radar information. The uncertainty is contained in the parameters of the dynamic system model in the case of a maneuvering target and in the presence of numerous marks caused by reflections from many targets or false alarms in the case of a complex target.

There is a class of goals that are characterized by both types of uncertainties. They include ballistic missiles (BM) and launch vehicles (LV) in the sites of their removal or in the active sites of the trajectories (AST) of their flight. The characteristic features of the movement of these objects are described in [1]. Moreover, a series of non-standard situations for radar tracking systems arise. Such situations are described in [2]. In this case, the main problems arise due to the large values of accelerations and their sharp changes, as well as due to the changing target composition during the flight.

A large number of foreign and domestic literatures are devoted to the solution of these issues. These issues are most extensively described in [3]. The range of approaches to solving problems of radar tracking requires the development of methods for assessing their performance. Accordingly, the scientific and methodological apparatus for testing the quality of IRS operation in the modes of trajectory processing of radar information to resolve the existing problem of tracking maneuvering and...
complex targets should also be developed; it will most fully take into account the features associated with both the movement of goals and the processing of information from them.

2. Research Method
The probability of target breaklock from tracking is used as an indicator of the effectiveness of the algorithms for radar tracking. It is calculated experimentally, and in the general case is estimated as

\[ p_{ss} = 1 - \frac{N_s}{N}, \]

where \( N_s \) is the number of successfully followed trajectories; \( N \) is the total number of specified trajectories.

There is a need to build a simulation model in accordance with a given performance indicator, focused on obtaining information about the quality of tracking algorithms by conducting simulation experiments. The result of each experiment should be information on successful or frustrated tracking of target.

The general methodology of the simulation process is described in [4]. The IRS functioning in the specified operating modes is reproduced in the basis of the model. The answer about the successful or failure tracking is formed depending on the given random influences and the specific initial data at the output, as well as the error vector of the measured and extrapolated coordinates. The probability of target breaklock from tracking according to the results of all experiments is estimated on these data; and generalized error vectors of measured and extrapolated coordinates are also formed.

They are compiled by averaging errors for each cycle of the tracking algorithm. Errors are introduced into the models of received signals in the form of random components distributed according to the normal or exponential law within the accuracy characteristics of IRS, as well as the addition of additive white noise and narrowband interference into these models.

The conceptual model is shown in Figure 1. As initial data for modeling are used:
- geographical coordinates of the start points and fall of the BM and LV;
- weight-dimensional, painful and design parameters and characteristics of existing and prospective BM and LV;
- parameters of applied emitted and received signals of IRS;
- tactical and technical characteristics of existing IRS;
- existing and prospective methods of detection and tracking of radar targets.

Block 1 of BM and LV parameters, includes the initial data on the launch parameters (coordinates of the start and fall points, as well as the quantitative composition of the flying hours and their time distribution) and the immediate parameters and characteristics of BM and LV.

Block 1 with block 2 (motion model of the maneuvering target) is the simulator of input influences for model of IRS functioning in the established modes. The output data of the input effects simulator are the coordinates of the state and target speed, as well as its reflective characteristics. The coordinates are dynamically checked for targets in the field of view in block 3. The reflected signals are formed at presence of them in block 8 on the basis of the output data. It is assumed that the first measurement (block 4) from the target occurs within 1 second from the moment of crossing the target of the lower barrier zone of the IRS.

A decision on the presence or absence of a target is made in blocks 9, 10 (detection and tracking models of IRS); the measured values of the target motion parameters are formed, which are compared in block 11 with the values laid down in motion model of the BM and LV. The result of the comparison is the measurement errors generated in block 19. Then, the formation of a correlation strobe is in block 12 and the imitation of the emitted signal is in block 13. The extrapolated values are also compared with the values in the motion model of BM and LV in block 5, resulting in extrapolation errors generated in block 14. Measurement errors and extrapolation errors are one of the indicators of radar operation in tracking mode.
The logical diagram of the conceptual model of the functioning of the radar

The processing procedure will repeat when the target hits into the formed correlation strobe. In this case, several targets can hit to the strobe, it will influence on the reflected signal. Since the peculiarity of this model is the assessment of IRS efficiency when working with maneuvering and complex targets, the criterion of completing tracking is the steady movement of BM on an unperturbed part of the trajectory. The presence of at least 10 consecutive marks from the target in inactive trajectory leg (ITL) at modeling is considered such a criterion. The criterion is checked in block 7. In this case, a decision is made on the successful completion of tracking; the target is breaklocked from processing (block 16). The initial information for these blocks is the IRS parameters and the parameters of the generated signals (blocks 17, 18).

Repeat extrapolation is performed in the absence of a target in the formed correlation strobe. At the same time, if the condition of the breaklock criterion performs, decision about the failure of the tracking will make (block 15). The target will reset from processing. This condition is checked in block 6. The absence of a target in the correlation strobe more than two times in a row, as well as the failure to fulfill the conditions for detecting a signal (at the too small received signal) can be used as a breaklock criterion. The output data of the model is information about successful or breaklock of
tracking (blocks 15, 16), as well as errors of extrapolated and measured coordinates of the target’s movement (blocks 14, 19).

3. Results and Discussion

A simulator of input influences is needed for the model of evaluating the effectiveness of trajectory tracking systems, which will physically adequately describe the movement of the target in question. There is a problem of construction of model of mass flight of the purposes which will consider the basic conditions of parametric a priori uncertainty of movement and will be the simulator of input influences for model of an estimation of efficiency of systems of trajectory tracking of the target.

The simulation is carried out for one rocket in the following order calculation of the required speed and angle of throwing, taking into account the correction for the rotation of the Earth, calculation of BM motion in the atmospheric section of the flight path, calculation of the BM motion on the off-atmospheric section of the flight path, calculation of BM motion on the passive part of the trajectory, calculation of the movement of exhaust stages and fairings. At the same time, the characteristic reflective characteristics of the targets are modeled for all sites. The calculation of the required speed and angle of throwing is made in accordance with [5].

The priority issue of modeling is an adequate reflection of maneuvers, the composition of the target, as well as the target situation in the IRS view area in accordance with the task statement. Sharp changes in speed and acceleration are important for trajectory tracking systems, so in addition to simulating the intervals between work stages, the movement of the head of the rocket after the reset of the spent last stage is simulated. The relevance of these calculations is justified in [2]. The requirement for the composition of the target is resolved by modeling the movement of the exhaust stages and fairing.

The model of BM motion in the atmospheric section of the active part of the trajectory (APT) is based on the results described in [1]. The atmospheric section includes:
- BM movement in the first stage work area;
- BM movement in the work area of the second stage to reset the fairing;
- uncontrolled movement of the fairing and exhaust stages.

The simulation takes into account the impact of the atmosphere at different altitudes, the rotation of the Earth, the earth's non-spherical, linear dimensions and shape of the BM, the movement of the BM between the steps, the movement of the separating parts of the BM. The basis of the simulation was the numerical integration of the equations of motion of the center of mass with an integration step of 0.08 seconds. The missing ballistic coefficients were obtained using [6].

The model of BM motion in the out-of-atmosphere region of the APT is also based on the results described in [1]. All motion parameters were calculated on the basis of this technique. The simulation was carried out taking into account the zero and first approximations of the height of the spherical layer.

Modeling of the passive site as a solution of the forecasting problem was carried out on the basis of works [1, 5]. The trajectories obtained as a result of modeling adequately reflect the data on nominal trajectories obtained by means of obtaining telemetric information [1], as well as flight descriptions of the missiles used on the sites: www.missilethreat.com/missilesoftheworld and www.designation-systems.net/dusrm/.

The most accurate description of the transformation of the IRS signal reflected from the targets should be a distinctive feature of complex and maneuvering targets due to the development of the model in order to solve the existing problem of tracking. The received radar signals tend to fluctuate [6, 7]. The average effective area of scattering (EAS) values were determined by the data specified in the tactical and technical task for the object of study for different target composition, as well as the peculiarities of the BM motion in different layers of the atmosphere and near space. The EAS in the calculations was given by a random number distributed according to Rayleigh's law with a specified average value per APT.
Also, the actual irradiation of the target by the emitted signal is taken into account when calculating the received energy and, accordingly, the complex Gaussian random amplitude. It is achieved by modeling the spatial position of the transmitting radiation pattern (RP) relative to the target location and the effect of this position on the energy of the reflected signal. It is very important at modeling not only adequate reflective characteristics of the target, but also radar tracking algorithms, because of it provides the formation of different energy values of the reflected signal depending on the accuracy of extrapolation of the target trajectory. Such a parameter as the minimum energy of the received signal is one of the tactical and technical characteristics (TTC) of the IRS and one of the criteria for the end of the tracking due to non-detection of the signal from the target when modeling radar algorithms. This approach makes possible to model the basic conditions of parametric a priori motion uncertainty for systems of trajectory tracking of targets.

The developed simulation model is designed to evaluate the effectiveness of IRS tracking algorithms. It is achieved due to the possibility of introducing any existing and promising algorithm into the imitation of the functioning of the IRS. The latter is implemented cyclically; each cycle simulates the operation of the signal and trajectory processor of IRS during one time unit, starting from the reception of the signal and ending with its emission. The time between clocks processing for a specific target is also determined by the performance characteristics of the IRS. The IRS tracking process includes the solution of a complex of tasks. These tasks are solved in each cycle of the simulation algorithm, namely: target detection, estimating its coordinates, linking the obtained marks to the trajectories, extrapolating the trajectory and forming correlation strobes. In addition, the tracking process is determined by the operating modes: target detection, confirmation of target detection, fastening of the trajectory, tracking itself and breaklock or end of tracking. It is necessary to be based on the available means and capabilities of the IRS, for example, on the type of antenna system, the number and type of measured parameters, types and parameters of the processed signals. Also it needs to decide on the choice of coordinate systems for filtering, extrapolating and forming correlation strobes, types of separation of directions in the view area, methods for adapting filter parameters to sudden maneuvers that interfere to reflections and to complex targets, approaches to modeling a tracking target and with types of choosing a base filter of assessment. Specific algorithms for radar tracking of targets are built taking into account all the existing restrictions.

Several algorithms of tracking of early warning radar used in the IRS were evaluated based on the simulation results [4]. Tracking quality was evaluated at various sections of the trajectories and in mixed flight in accordance with the given requirements and input data that determine specific trajectories depending on the start and fall points. The evaluation results are shown in Table 1.

| Table 1. Probabilities of missed targets with tracking for various algorithms |
|---------------------------------------------------------------|
| **\( \alpha - \beta - \gamma \) algorithm** | **Kalman linear filter** | **Advanced Kalman filter** | **Quadratic algorithm** |
|---------------------------------------------------------------|
| In the AST | 0.76 | 0.65 | 0.56 | 0.54 |
| In the ITL | 0.15 | 0.07 | 0.065 | 0.05 |
| During the transition from AST to ITL | 0.28 | 0.21 | 0.18 | 0.176 |
| During the transition from ITL to AST | 0.89 | 0.69 | 0.61 | 0.52 |
| In mixed flight | 0.64 | 0.43 | 0.35 | 0.31 |

The lower the probability of target failure from tracking, the better the performance of tracking algorithms. The simulation was carried on passive trajectory section by setting flight paths, taking into account their unambiguous hit in the radar field of view on the ballistic section. You can also use a simpler input simulator based only on the ballistic flight of targets. In the same way, the movement on the active trajectory section was simulated – taking into account the flight of targets for at least 40 seconds with the engines turned on. The flight simulation with transitions between active and passive
sections is the most suitable for real conditions. In the simulation, it was assumed to move active trajectory section for at least 10 seconds, after which there was a transition to the passive section. Less interesting from the practice point of view, but no less interesting from the science point of view, the case of transition from passive to active site was also modeled. In this case, a modified input impact simulator was used that was not linked to the start and fall points. Trajectories with different parameters of movement on the Kepler arc, uniquely passing through the radar viewing area, and located in such areas for at least 10 seconds, were set, after which the engine activation and controlled flight on the non-atmospheric section of the trajectory were simulated according to the method described in [1]. In the described cases, the flight of single ballistic missiles, as well as their spent stages and fairings, was simulated.

Flight in mixed mode involves simulating the flight of targets on different parts of the trajectory using the developed flight simulator, which sets the spatial and temporal distribution of targets, with the expectation of unambiguous passage of targets through the radar viewing area and being in it for at least 40 seconds. Table 1 shows the results of calculating the probability of targets tracking failures, taking into account the simultaneous presence in the field of view of 25 targets-ballistic missiles, their spent stages and fairings.

4. Conclusion

The obtained data as a result of modeling show that on passive sections of the trajectories a high level of quality of target tracking is provided for existing algorithms. The requirements for the quality level of such algorithms, as a rule, are determined in the tactical and technical tasks on the radar. The probability of frustrating targets with tracking should not exceed 0.2 for most tools. It can be stated that these requirements are not fulfilled for the non-ballistic flight sections of the BM and LV based on the simulation results. It indicates the inconsistency of existing processing methods with the requirements for the quality of maintenance and determines the need to develop new methods that provide a given quality indicator.

The simulation allows to set various options for the phono-target environment in the IRS view area; determine the presence of targets in a given area of space at a given time, imitate the reflective characteristics of targets; check various target tracking algorithms, obtain an estimate of the probability of a target collapse with tracking.

The model adequately describes the functioning of the IRS in various operating modes (detection, measurement, tracking), the behavior of targets in aerospace, and allows to evaluate the effectiveness of radar tracking algorithms.

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