Air Navigation: Optimisation Control of Means Cueing of the Air-Traffic Control System

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Abstract—**Article is devoted to one of important problems of navigation of aircraft - increase of the effectiveness of air traffic control system at the expense of cueing perfecting. In process, based on methods of the optimal control theory, is offered approach to optimization of functioning of measuring means supplying by trajectory information of motion variables of air vessels control system of air traffic. Results of simulation allowed to draw conclusion of essential increase of cueing efficiency of such system.**

I. INTRODUCTION

World statistics show that the intensity of air traffic in all countries is growing rapidly. This circumstance urgently requires the conduct of new studies aimed at maintaining the safety of aircraft [1].

Scientific-technical progress in civil aeronautics is displayed in a few directions. First of all, it relates both to increase of diversity of used aircrafts types (beginning with small commercial aviation and finishing by wide-bodied airbuses and supersonic airliners) and to increase of total volume of air traffic accompanied by growth of the number of routes and their solid length. The density of air traffic is constantly increasing, which leads to the limiting values of the throughput of modern air control systems, the decrease in the efficiency of air traffic controllers [2].

Three main aspects, namely safety, regularity and economical efficiency of flights, are linked to each other closely and substantially depend on management efficiency by air traffic (ATC). By radical solution method of emerging problems at the same time, as it was found out as early as 50s of last century, is automation of the collection, transfer and information processing of air picture.

The main and main component of automated control systems of air traffic are Measurement and Information Systems (the facilities for active and passive radar-tracking observation, radio and satellite navigation systems etc.).

As early as 1975 in [3] it was noted that already then basic opportunity of construction of entirely automatic system of ATC working without participation of the person-operator existed, and the role of the dispatcher in such system can be reduced only to integrity monitoring of the system. At the same time interference to it work is necessary just at occurrence of situations not provided by information processing program. However at realization of such entirely automated system arose serious difficulties both technical, and technological, psychological, legal and other sort. By now such difficulties mainly are overcome.

Creation of new generation of automated systems of air traffic control (AS ATC) and the systems of information processing automation became possible due to development of new information technologies based on modern program and hardware computer means [4]. Scientific development base consist in control theory methods, supervision and information processing. Opportunities of modern computer systems allow to realize algorithms and programs as application of fundamental mathematical theories which still recently were beyond the reach of use in AS ATC and for this reason (as thought the designers of information systems) related to category of abstract. It relates, primarily, considering in the previous sections to elements of present-day theory of control automation and information processing in statistical Measurement and Information Systems.

Algorithms realized in earlier of developed ATC of primary and secondary processing of radar-tracking information, are based on spectral-correlation methods of filtration and evaluations (in particular such, which use the Neumann-Pearson criterion).

Methodological base of creation of modern systems of ATC is accounted for by new information technologies.

All aircraft are moving in the air space with terminal speeds. They need to hold safe intervals and separation standards. Since every element of the air space is limited, then, accordingly, it can at the same time "contain" a limited number of aircraft.

Consider the description of the flow of aircraft (AC) and its passage through the element of air space.

As with any transport system, the AC stream should be considered as orderly movement of bodies in real space.

Let's highlight an element within a certain limited amount of space P, in which moves the material flow in the amount Q with the translational (road) speed V, vector which is directed along the axis of the element.

Then, by definition, the flux density is given by

$$\rho = \frac{Q}{P} \ . \quad (1)$$

when $V = const$ expression (1) holds for $Q = const$, and for $Q = var$. In other words, we are talking about the instantaneous value of density $\rho(t)$. When $Q = const$ and $P = const$ there is a stationary process. It is natural to consider Q changes as a result of the imbalance between input and output streams from it. Let by the time dt input stream is dQ', and the output dQ^0. Then the intensity of the incoming and outgoing flows are equal, respectively

$$\lambda' = \frac{dQ'}{dt}, \ \lambda^0 = \frac{dQ^0}{dt} \ . \quad (2)$$

It's obvious that, $dQ = dQ' - dQ^0$, and at $\lambda' = \lambda^0 = \lambda \ \ Q = const$. In this case λ there is flow-through rate.

Known [5], [6] that in practice the intensity and the traffic density are calculated by the number of input and output AC.

The main attention should be paid to the airways and their elements. The beginning and end of the track section may coincide with any of these elements.

Consider the section of the route at this echelon of fixed length L. Given the limited width of the track and the impossibility of overtaking during a flight at the same level as a parameter corresponding to the volume of P (1), in favor of its length L. Let the intensity of the incoming and outgoing flows through, λ' и λ^0 respectively.

The parameters λ' и λ^0 are essentially functions of time, but to reduce the recording time t is omitted in this notation.

Relation (1) corresponds to the average (cumulative) density $\rho = \frac{Q}{L}$, and with uneven distribution AC along the length of the route - the differential density $\rho = \frac{dQ}{dl}$, which generally differs from the integral.

From ratios (1, 2) should be

$$\lambda = \frac{Q}{L} V, \ Q = \lambda \frac{L}{V} = \lambda \theta ,$$

Where, $\theta = \frac{L}{V}$ – time of flying over the distance L.

In accordance with the flight and technical characteristics of the AC is usually divided into several high-rise layers, the best for certain types of aircraft [10]. So, for the upper space velocity V can be 900 km/h, for an average of 750 km/h, and for the lower 475 km/h. In this connection, we can assume that each track (or part of the route) corresponds fairly certain speed V. Consider the impact of the spread of the actual velocity.

As the two main parameters that characterize the element of air space - part of the route, it is advisable to take the length L and the speed of traffic on the track V or their ratio $\theta = \frac{L}{V}$. This value can be considered as the length of time that is a parameter having the dimension of time.

It is easy to see that the derived ratios apply not only to the airways, as well as local airlines, routes, corridors, i.e. to those elements, where the flow cannot be delayed. Elements such as airports, where there is an accumulation of aircraft required for its analysis of a different approach.

By definition, the bandwidth is the maximum allowable rate, i.e.

$$\lambda_m = \frac{V}{d_m} , \quad (3)$$

where d_m — is minimum allowable spacing between adjacent AC is determined by the norms of security of longitudinal separation.

From analysis ratios (3) and [7], [8], [9], [10], [11], [12] it is necessary important conclusion about one of the principles of the air-traffic management - for increase of traffic capacity of air corridors need to lower a minimum admissible interval between adjacent aircrafts (A/C), and it needs increase of determination accuracy of current location and parameters of aircraft movement for preservation of given safety of along track separation [13].

II. Theoretical basis

A. Target setting of cueing effectivization of the air-traffic control system

Supervision for mobile objects is practically always implemented at deficiency and distortion both a priori knowledge and current (operational) information. At such ambiguity arise the tasks of the summing-up and motion variables of observable aircraft.

The problem of supervision theory consists in construction of the best, in determined sense, processing technique of co-ordinates measurements of mobile object, accessible to measurement. Results of supervision should contain information, sufficient for implementation of management functions.

The subject of theoretical consideration should be tool methods of supervision of mobile objects. Complexity of the problem is caused by variety of circumstances. On the one hand, grows the circle of controlled, mobile objects being subject supervision. At that, along with increase their diversities on types (airy, cosmic, ground-based etc.) and expansion of the spectrum of their properties and specifications (speeds, heights, maneuvering capabilities etc.), grow of requirement to accuracy and the reliability of results of supervision. On the other hand, hasty growth of supervision hardware, navigation and communication using the latest computer technologies, allows using widely results of theoretical development in the domain of information processing, including such, which earlier were beyond the reach of practical application by virtue of limited opportunities of computer facilities.

Specified circumstance relates to full extent to the domain of control of air traffic, where for control of A/C in airspace or on Earth use wide array of navigation means and supervision.

For satisfaction of modern, high requirements to developing systems of ATC it is expedient to use all arsenal of the control and supervision theory [7, [8], [9], [10] and for realization of algorithms created on this base, it is necessary to use advanced achievements of computing, program and hardware of new generation.

In the common form the supervision problem is considered as the task of calculation of current co-ordinates of mobile object in accessible to measurement sizes.

It is known that the problems of supervision and controls have the common nature. This universality is displayed in property of duality between control and supervision.

ATC system, as a whole, should be considered as difficult system which is subject to the common laws of the theory of control. For manufacture of the decisions and controlling impacts on the basis of feedback it is necessary knowledge of variable conditions of the system - phase controlled devices co-ordinates, as which act both single A/C, and their flows.

For efficient control it is necessary knowledge of sufficient number of phase co-ordinates. At that, than higher requirement to dynamic accuracy of control procedure the greater number of phase co-ordinates should be measured. However in actual practice, as it is known, not many co-ordinates are accessible to measurement, but those for which there are the appropriate indicators, turn out noises. Missing co-ordinates it is necessary to calculate, that is, to receive with the aid of not direct, but indirect measurements.

So, for example, business consists with derivatives of time from by measured co-ordinates, resulting in additional growth of interference level. We will note that specified difficulties exist even then, when the interference level and the model of observable object are known enough well.

Way out consists in co-ordinates definition not only from their instant measuring values, but also with use of some pre-history of their change on the previous time interval.

In view of ambiguity caused by specified features of measurements, for operations of definition of determined state parameters of dynamic system should be applied estimation which assumes presence of ambiguity as a result of measurement, and methods and algorithms should be considered in [8].

Inasmuch as in supervised zone there is not individual object, but some quantity (number of A/C can reach a few tens or even hundreds), messages flow containing information of situation (co-ordinates) of objects, has irregular character (in view of losses and untrue signals).

Signals detection tasks (messages) bearing information of condition of the system, including their detection, classification, filtration and other operations, relate to primary processing of radar-tracking information. Exception is accounted for just by some tasks of decoding and codes connected, first of all, with display of radar-tracking information.

Supervision for objects reloadable in the space, at interferences and in the conditions of ambiguity regarding their future behavior, is reduced to the evaluation of state parameters of dynamic system that represents mathematical model of measurement object. It is necessary to take into account that supervision is implemented without direct contact with observable object. Therefore process of supervision includes transfer and transport of signals bearing information, message of deployment of the object or it changes.

Relatively to the ATC area, as surely as in the other control problems of vehicles, it is necessary to say of quantity (flow) of observable objects and, at bottom, about a few measures which form a measuring system.

In general terms, diagram of supervision can be presented as, shown on the Fig.1.

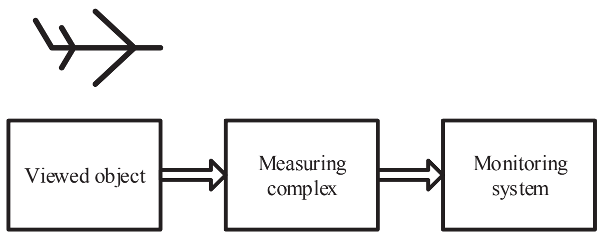

Fig.1. Diagram of supervision for air vessel

By sources of information are following measuring complexes: radars - are primary and secondary; on-board navigation systems and on-board navigation complexes including instrument, inertial, satellite and other; other equipment which enters a flight and navigation computer complex of modern planes of civilian aircraft.

Monitoring system functions hopes in above-ground complex of automatic means, supervision and reflection or to automated system (AS) of ATC.

Process of organization and operational administration by air traffic is possible following receipt of necessary information (general diagram is illustrated on Fig. 2).

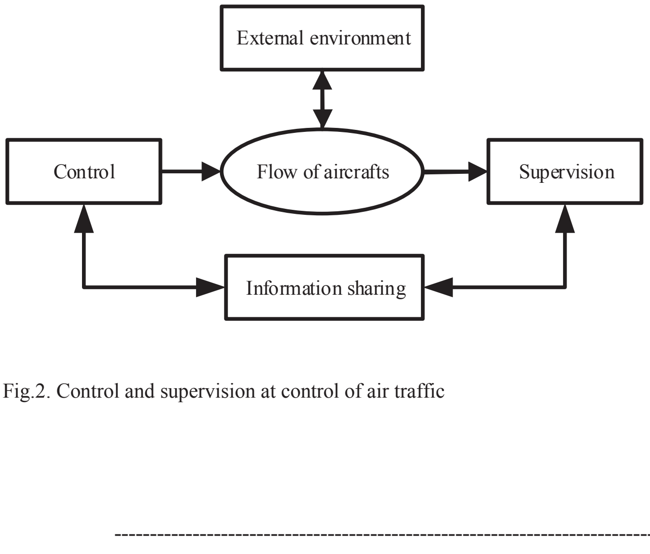

Fig.2. Control and supervision at control of air traffic

The main task of supervision in the systems of aero-control is in decrease up to the minimum of occurrence of object loss, that is, wrecking of supervision. The problem of accuracy increase of location and parameters of movement A/C, as end in itself, departs to the second plan, and to consider it makes sense only from the standpoint of achievement of specified main purpose. Really, at ideal observance of desired path within the limits of norms airborne separation, at nominal specifications of the main source of the information of A/C movement, in perfect conditions check for air traffic does not cause serious difficulties.

Vital problems arise in the conditions of ambiguity with allowance for receipt of the information discrete in time of the arrangement of A/C, as well as ambiguity of it movement in the area of airports and implementation of maneuvers at transition from one echelon to other.

Analysis results of application of media ATC show necessity of the account of two main sources of ambiguity:

- external irritating factors, false actions of the crew or malfunction (rejection) of on-board systems result in deviation from desired path of movement, to change of nature and parameters of observable trajectory on the interval between adjacent reports;
- co-ordinates measuring errors, as well as parameters of movement caused by impact of factors of environment, interferences and errors of indicators, the systems of transfer and data processing.

It is known that for accounting of specified factors it is necessary to generate an optimum system of information processing.

Inasmuch as at supervision for aircraft takes place the problem of steady tracking by radar-tracking means of such vessels on the section of landing approach in runway, then at development of the subsystem of supervision expediently to apply methods of adaptive recursive filtering which are considered in [8], [10].

B. The directions of cueing effectivization of the air-traffic control system

Air-traffic control system is organized for establishing and maintenance of order in airspace, for prevention of dangerous getting closer and collisions of air vessels among themselves and with on shore obstacles, as well as for supplying by the information and consultations, needed for a safe performance of flights and the messages of the proper authorities about A/C requiring rescue and rendering them of necessary aid [5], [14].

Traffic department has organizational structures consisting of three hierarchical levels [5], according to which it activity is classified into three main types (Fig. 3). On top reporting level are solved the organization problem of air traffic and aircraft flight support on all phases of movement of A/C, the tasks of construction of control elements, as well as interactions between ATC of various departments and flight support services. On average level are solved the problem of long-term and preliminary planning of air traffic and direct supplying of execution of this plan. On the lowest level are solved the problem of operating control by air traffic at all stages of navigation.

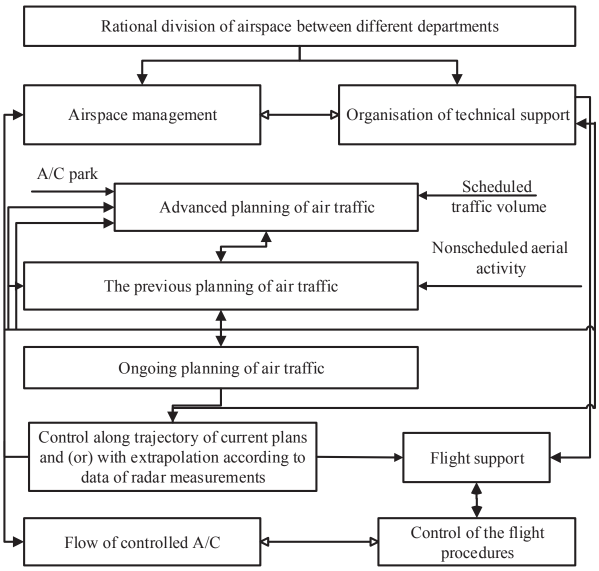

Fig.3. Flow diagram of operation ATC system

Operating control by air traffic is intended for supplying of movement of each A/C pursuant to accepted plan of it flying, the appropriate to the criteria for safety, regularities and economical efficiency, as well as for reasons of flight safety A/C, that is non-admission of their approach closer to the intervals less given on criteria for safety on all phases of flying by the way of monitor and control of motion. In zones with high density of air traffic to the system of operational ATC are made great demands to accuracy of the intervals endurance of passing A/C. Accurate intervals endurance which is based on timely receipt of trustworthy information about A/C location, is the base safety of movement.

Control can be implemented by two main methods: along trajectory of current plan and with extrapolation according to radar measurements. Choice of control procedure depends on, in what zone flight is executed, and is defined by specific features of flights in these zones. From all activities of the traffic department the most difficult is operating control, as first, exactly in it are reflected specific features of air traffic - dynamism of processes and impossibility of their stoppage, and secondly, processes of monitoring intensification, inevitable at increase of traffic density, is limited by opportunities of dispatcher.

In works [7], [8] it is shown that tasks performance of operating control by the dispatcher functionally depends on parameters definition roughness's of trajectories A/C by radar aids, that it is possible to imagine as expression

$$K_D = f\left(\sum_{i=1}^{N} \sum_{j=1}^{M} h_{ij} \sigma_{ij}^2 \right) = f\left(\sum_{i=1}^{N} tr\left(\mathbf{h}_j^{\mathrm{T}} \mathbf{\Psi}_j \right) \right)$$

where N – is the number of aircraft, being controlled by the dispatcher, M – is the number of necessary trajectory parameters for aircraft motion characteristic, σ_{ij}^2 – dispersions of estimations errors for the appropriate aircraft motion characteristics, $tr\left(\mathbf{h}_j^{\mathrm{T}}\mathbf{\Psi}_j\right)$ – weighted covariance motion characteristic estimation errors matrix trace for *j*-th aircraft, $\mathbf{h}_j$ – weight coefficient matrix for accounting of importance of estimation accuracy for individual motion parameters for *j*-th aircraft.

It is known [6], that function $f(.)$ more often can be represented as follows

$$K_D = \exp\left[-\left(\sum_{i=1}^{N} tr\left(\mathbf{h}_j^{\mathrm{T}}\mathbf{\Psi}_j\right)\right)\right].$$

Thus, it is necessary to provide minimization of the parameter estimation errors of the aircraft path, which are obtained during radar metering, in order to increase quality of the dispatchers aircraft flow control.

In work [15] problem of the radar complex control was considered from the system positions first. It was shown, that the performance criteria of the radiolocation complex (RLC) should be matched with higher-level system criteria. To synthesize control algorithms information approach is used, wherein target information entropy on different RLC functioning stages is the main criteria. However this approach, considering current status of the optimal control theory, does not allow us to obtain effective solutions for RLC ATC in terms of difficult air situations. In work [10] main approaches for the RLC control were considered. These approaches are based on current objectives solutions and control, and do not consider long-term efficiency. Specifics of the ATC are also not considered. In work [11] an approach for air defense missile system RLC operation optimization is offered, but ATC operation specifics are not considered.

The task is to design method for automatic RLC control system ATC that considers specific for these system limitations.

Using known coordination methods for multilevel hierarchic systems, we are able to show, that the brightness attribute for the control at aircraft escort phase is matched with the efficiency attribute of the higher level system and can be expressed as follow [10], [12]:

$$J = \sum_{i=1}^{N}\sum_{t=1}^{T} tr\left[\mathbf{h}_i^{\mathrm{T}}(t)\mathbf{\Psi}_i(t)\right].$$

Here $tr\left[\mathbf{h}_i(t)\mathbf{\Psi}_i(t)\right] = \sum_{l=1}^{k} h_i^{ll}(t)\Psi_i^{ll}(t)$ is the trace of the matrix product $\mathbf{h}_i(t)$ and $\mathbf{\Psi}_i(t)$ that characterizes weighted values of coordinate's filtration error of the *j*-th object. Herewith weight matrix $\mathbf{h}_i(t)$ determination depends on aircraft escort and search methods during escort, and also on decision-making method for air traffic control.

The problem of statistical control RNC, functioning in the mode of estimating the parameters of the observed processes or objects is the task of the binary programming. The peculiarity of the problem lies in its linearity, as indicator of the quality of management, as well as the dynamics of the equation process is optimized, are nonlinear. Thus, to obtain an analytical solution is not possible. For its solution can be applied variety of numerical methods for solving optimization problems. Most of these techniques to date are presented in publications in the form of a series of algorithms that take into account features of computer realization of this class of problems.

Designed for solving the problems of integer algorithms can be divided into two groups [10].

The first group consists of sorting algorithms. These algorithms essentially use the fact that the integer variable is a finite number of values. Simplifying the situation, it can be said that the sorting algorithm is a set of rules which eliminate the major part of feasible solutions and leads to an optimal solution by analyzing a small number of situations. Advances sorting method essentially based on the calculation of the machine, as well as researchers intuition.

The second group of algorithms may include algorithms cutoff. In these algorithms in different ways we build a linear problem, the best solution that meets the requirements of integrality. It uses a working hypothesis as to what the problem simplex method is numerically solved well or other methods developed to date. Building effective cut-offs and acceleration of convergence is the major issues in the method of cutoffs.

With the help of algorithms, both the first and the second group can be an exact solution of the problems of observation control. However, all hitherto existing methods cannot be used in the algorithmic providing real-time control systems, since the solution of such problems requires significant time costs, which are measured in tens of seconds a small amount of controlled parameters and tracked objects (5-10) and a clock for real multi-functional RNC, when the number of control parameters can be up to several dozen at a number of tracked targets up to several hundred. Considered in [10] the method of principal faces, allow solving such problems, but it still requires further development to the practical application of real-time control systems. It should be borne in mind that the shorter control cycle, the more effective management of the facility. Practice shows that statistical VIC control loop should be unity seconds. During that time should be formed on all of the managed subsystem influence of such a system for controlling the mode of observation can be allocated no more than 20-30 percent of the time control cycle. Thus, precise methods cannot be used in practical control algorithms.

For practical purposes it can often be limited to about monitoring solution management tasks. This is explained by the fact that the construction of the approximate solutions is usually associated with lower computational cost than building an exact solution. In addition, the construction of an exact solution of the model problem is not always fundamental, because in the construction of a mathematical model of a real process is a simplification, and, accordingly, the practical problem is replaced by another model problem, exact solution which, strictly speaking, does not coincide with the exact solution of practical problems. Given the dynamic nature of the observations of management tasks to approximate their solutions can be used algorithms based on the discrete analogue of the maximum principle (minimum). Moreover, given that the controlled object is most clearly and simply written in a matrix form, it is advisable to apply the principle of maximum (minimum) in a matrix form.

Development of control method should take into account the specifics of the functioning of the statistical VIC in observation mode for objects or processes whose parameters should be evaluated.

Typically, to obtain an analytic solution of the problem of optimal control of process monitoring statistics VIC for the object (process) in most cases cannot be (unless the use of such information obtained processing filters on the observed processes (objects), where the dynamics of the covariance matrix of error estimates of the parameters described by linear equations). Therefore, it is advisable to apply numerical methods for its solution.

The universal method of solving complex optimization problems is the method of successive approximations. However, in the test case, an object that is optimized is dynamic. Dynamic programming principle and the maximum (minimum) method can be used to optimize such processes. Direct application of these methods for the synthesis of optimal control complex nonlinear multidimensional complexes, which are statistical VIC usually, doesn't result in a closed form solution.

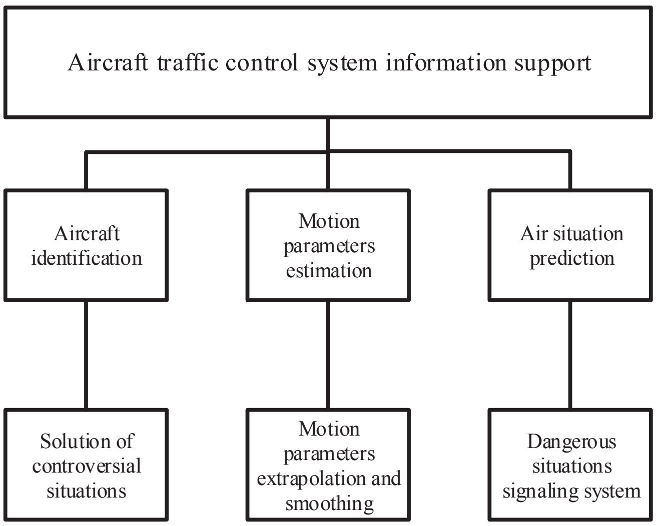

Fig. 4. ATC information support

Therefore, there can be proposed method for solving this class of optimization problems, based on a combination of discrete minimum principle and the method of successive approximations.

Method and algorithm for similar optimizing problem solution are designed in [7], [11].

III. Results

The simulation was conducted in order to obtain estimation of efficiency of the designed optimal RLC ATC control method and algorithm in aircraft escort mode. The method of RLC equal-probing (distribution of power resources) was used as a basic one for comparison, which is primary method for real radar complexes in terms of difficult air situations nowadays.

Usage of the designed method for RLC ATC gives us 10 – 34 percent gain in parameters of escorted objects estimation accuracy, compared to a basic method. Thus, the automation of the AS ATC control by information tools and usage of the information processing algorithms can result in more effective problem solving for ATC information support (Fig. 4).

IV. Conclusion

During this work next main results were obtained:

- The approach for complex information processing system and AS ATC control by information tools was offered, which based on appliance of the methods and algorithms designed in [5], [6], [7], [8].
- Mathematical formalization of the optimal AS ATC radar system control problem was conducted.
- An approach for the optimal RLC ATC control was offered that differs from known ones and allows to consider aircraft motion specifics on different phases, and to make the rational solutions for air traffic problems in general.
- Offered control and aircraft motion parameters information processing methods allows us to increase quality of the information support for AS ATC by 10 – 34 percent.

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