# MONITORING OF GEO SATELLITES

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## ABSTRACT

Cataloguing of GEO satellites commenced in Russian Space Surveillance Center (SSC) in the eighties. The permanent process of enhancement of software tools for catalog maintenance is proceeding since that time. The present paper describes the current status of this software complex.

## 1. INTRODUCTION

The papers [1,2] describe the general structure, characteristics and the algorithms for maintenance of the catalog of LEO (perigee altitude less than 3000 km) satellites in Russian SSC. The present paper treats the same issues for satellites in GEO. The domain of the phase space will be considered geostationary in case the orbital parameters satisfy the conditions $1-\delta T < T < 1+\delta T$, $0 \leq e < \delta e$, $0 \leq i < \delta i$, where $T, i, e$ - orbital period, inclination and eccentricity, $\delta T$, $\delta i$, $\delta e$ - constants.

First we analyse the initial background data, describing the conditions for catalog maintenance. These data include the characteristics of the sensors and the characteristics of satellite motion. Then the general scheme and its components are described, in particular, the algorithm for primary determination of orbits, the algorithm for assigning the measurements to cataloged satellites, the algorithm for updating the orbits using the data of the measurements, the procedure for planning the observations and calculating the target indications for the sensors and also the process of preliminary tracking of new satellites, arrived in the catalog.

In the course of the study we permanently compare the resulting procedures with the process of maintenance of LEO satellite catalog and analyse the observed difference.

## 2. SENSORS AND MEASUREMENTS

Currently Russian SSC uses the optical sensors network [3]. The major features of this network:

1. The sensors of the network do not provide the complete coverage of GEO ring.
2. All the stations operate with significant gaps, which may be as long as several months.
3. The optical sensors measure the angular coordinates of a satellite - the right ascension $\alpha$ and declination $\delta$ in the local equatorial coordinate frame. The errors of single measurements normally are within the range $1''$-$10''$. However the optical sensors do not measure the range. Thus the acquisition of the complete six-dimensional vector of the same order of accuracy, as for the radar measurements of LEO satellites, requires several single measurements (marks) within rather long time interval. The analysis revealed, that the orbit can be determined with the accuracy, sufficient for SSC in case the marks belong to at least two nights and for one of the nights there are at least four marks, uniformly spaced in time within the interval not shorter than 2-3 hours. This is the requirement of the SSC to the measurements of optical sensors. However, due to a set of reasons, the measurements do not always satisfy this requirements. More than one half of the measurements are acquired during only one night and do not cover the required time arc. In this case one or two (out of six) orbital parameters can not be determined with sufficient accuracy.

## 3. SATELLITE MOTION

The observed objects are moving in space. The model of their motion is needed to design the catalog maintenance algorithm.

The orbital parameters $\mathbf{a}$ of any space object satisfy the system of the first order differential equations of motion. Thus $\mathbf{a}(t) = \mathbf{U}(\mathbf{a}(t-\tau), \tau)$. The precise functional relationship $\mathbf{U}(\mathbf{a}, \tau)$ is not known and in practice the approximate relationships $\mathbf{U}_0(\mathbf{a}, \tau)$ are used, which determine the specific algorithm for prediction of orbital parameters.

Real prediction errors $\mathbf{V} = \mathbf{a}(t) - \mathbf{U}_0$ are generated by the inexact account of the perturbating factors and comprise two components: methodical error $\mathbf{V_1}$ and the non-removed error $\mathbf{V_2}$. The methodical error is the result of the inexact account of the considered perturbating factors. The non-removed error originates from no account of certain real perturbating factors.

The three basic requirements to the prediction algorithm are as follows:

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1. real prediction errors should not make the correct correlation of measurements to cataloged satellites impossible;
2. real prediction errors should not exceed the values, defined by the maximum permissible errors of target indication for optical-electronic sensor;
3. the CPU-time of the computer code must be acceptable.

Since the basic operations of the algorithm (correlation of measurements with cataloged satellites and orbit updating) rather often must be performed involving the measurements and orbits significantly distant in time (up to several years) the creation of the relevant procedure is not an easy task. However, we managed to solve it.

We won't treat this algorithm in detail here, since it is described in papers [4,5]. The basic characteristics of this algorithm are as follows.

1. Methodical errors of the prediction algorithm do not exceed $3'$ ($\approx$38 km) for propagation intervals up to four years.
2. The real prediction errors for propagation intervals up to 500 days do not exceed $1'$ ($\approx$12 km) for 50% of the passive satellites of the real catalog.
3. The computation time $t_{comp}$ of the propagator (computation rate 1 millions of average operations per second) can be assessed using the formula $t_{comp}[s] = 0.01N_{st} + 0.003N_t$, where $N_{st}$ - is the number of the integration steps (the step for the integration is chosen within the range 10 -20 days); $N_t$ - the number of the points for which the propagation is fulfilled (within the total prediction interval).

The processing of measurements rather often requires the propagation of all the orbits of the catalog to a certain epoch. This operation essentially simplifies the data processing. The characteristics, presented above allow to fulfill the propagation of the whole catalog for one year in 1.5-3.0 minute. This is quite acceptable.

## 4. THE GENERAL ALGORITHM

The structure of the catalog maintenance algorithm in general is similar to the structure of the procedure, used for LEO satellites. However, some specific features, determined by the structure of the initial data, do exist.

The measurements, received by the SSC enter the procedure of **primary orbit determination**. For each measurement the parameters of the orbit and the errors of their determination are estimated on the basis of the single measurements (marks) and the a priori data.

Then for each measurement we determine, whether the satellite, which produced it exist in the catalog, i.e. the task of **assigning the measurements to the cataloged satellites** is solved. As a result the measurement becomes either assigned (correlated) to certain satellite, or remains free (uncorrelated).

The correlated observations update the orbital parameters of the satellites that produced them, i.e. the task of orbit **updating** is solved. If we manage to correlate the measurements to certain satellite and update its orbit regularly, the satellite is monitored or **tracked**. When the flux of the measurements of certain object ceases or weakens significantly, the tracking of the satellite may stop. The break of tracking occurs.

The uncorrelated measurements are included into the catalog as new satellites and participate in the tracking process together with the other cataloged objects.

At the initial stage of this process - the **preliminary tracking** - the new satellite is identified with the objects, already present in the catalog and with the lost ones. In case the satellite is identified with the previously cataloged object the data on this satellite are renewed and its tracking is thus recovered. When the decision is made that the orbit belongs to a new, not previously cataloged satellite, its origin (international designator) must be determined, i.e. the **satellite identification** task must be solved.

In distinction to the catalog maintenance process for LEO satellites the interaction with the network of optical sensors includes the feedback, i.e. the sensors work under the control of the SSC. The feedback means **planning of observations and calculation of target indications** for the sensors. The objects for the assumed future work of any optical station are selected and the respective target indications are calculated.

The following sections 5-9 describe the basic algorithms used for maintenance of the catalog of GEO satellites in more detail.

## 5. PRIMARY ORBIT DETERMINATION

The detailed consideration and analysis of the algorithm for primary determination of orbits is given in the work [4].

The estimation of the orbital parameters is the point of the minimum of the functional

$$\begin{aligned}\varphi(\mathbf{a}) = \sum_{p=1}^{r} \left[w_{\alpha p}(\alpha_p - \alpha_{p}(\mathbf{a}))^2 + w_{\delta p}(\delta_p - \delta_{p}(\mathbf{a}))^2\right] + \\ w_{a1}(a_1 - a_{1a})^2 + w_{a2}(a_2 - a_{2a})^2 + w_{a3}(a_3 - a_{3a})^2 + \\ w_{a4}(a_4 - a_{4a})^2 + w_{a5}(a_5 - a_{5a})^2 + w_{a6}(a_6 - a_{6a})^2,\end{aligned} \tag{1}$$

where $(\alpha_1,\delta_1)$, $(\alpha_2,\delta_2)$,...,$(\alpha_r,\delta_r)$ - the marks of the measurement with time references $t_1 \le t_2 \le ... \le t_r$; $\alpha_p(\mathbf{a}),\delta_p(\mathbf{a})$ - functional relationships between parameters $\alpha_p,\delta_p$ of $p$-th mark and parameters $\mathbf{a}=(a_1,a_2,...,a_6)$ of the satellite; $w_{\alpha p},w_{\delta p}$ - the weights of the components of $p$-th mark (the values, inversely proportional to the variances of the components' errors); $\mathbf{a}_a = (a_{1a},a_{2a},...,a_{6a})$ - the vector of a priori values of orbital parameters; $w_{a1},w_{a2},...,w_{a6}$ - the weights of the components of $\mathbf{a}_a$ (the values are inversely proportional to the variances of the errors of these components);

For the vector **a** of orbital parameters we take the six-dimensional vector of the elements $\mathbf{a} = (\tilde{\lambda}, L, p, q, \tilde{h}, \tilde{k})$, derived from the known Keplerian elements $M$, $a$, $i$, $e$, $\Omega$, $\omega$ using the formulas $\tilde{\lambda} = M + \omega + \Omega$, $L = \sqrt{\mu a}$, $p = \sin(i/2)\cos\Omega$, $q = \sin(i/2)\sin\Omega$, $\tilde{h} = e\sin(\omega+\Omega)$, $\tilde{k} = e\cos(\omega+\Omega)$, where $\mu$ - gravitational constant. Vector **a** is referred to the certain time $t_m$ $(t_1 \le t_m \le t_r)$. The components of the a priori vector $\mathbf{a}_a$ are the average expected values for GEO satellites.

The initial approximation, used in the minimisation of the functional $\varphi(\mathbf{a})$ is constructed. The algorithm is the modification of the known Laplace's technique [6], which in its pure form turns to be inefficient due to high sensitivity to the errors in initial data. The essence of the improvement is to gain the advantage from the a priori data on the orbital parameters. Our algorithm uses only the a priori data on the semi-major axis i. e. it is considered that $a = a_0$, where $a_0$ - is constant, equal to the semi-major axis of GEO satellite with orbital period equal to one day. Thus the developed technique can be used not only for the objects within geostationary ring, but also for other important types of objects, for example for satellites with half-day orbital period. The derivation of the formulas, computational aspects and the analysis of the performance of the procedure (for real measurements on various classes of satellites) is presented in the paper [4].

Then the minimum of $\varphi(\mathbf{a})$ is sought. The minimisation uses the multi-pass scheme, selecting during each pass the abnormal components of all the marks using the normalised residuals between the measured and assessed values. For the first pass all the marks are taken with the weights calculated according to the variances of the errors. Before each next pass the components of the marks are tested for abnormality by comparing to the threshold $c_a$ the squared normalised residual (the respective component in $\varphi(\mathbf{a})$) for the point of the minimum, obtained at the previous pass. The weights of the discovered abnormal components are set to zero and the normal components of the marks, mistakenly excluded from the processing previously are re-introduced into the process by the recovery of their weights. When the certain step of minimisation shows that the weights are chosen correctly the passes finish. The algorithm for minimisation of $\varphi(\mathbf{a})$ used at each pass is described in [2,4].

If the finished cycle of minimisations *yields* the decision, its reliability is tested. The decision is considered *reliable* in case both components of at least three marks have completely inscribed into the determined orbit and the share of the marks acquired during each night, for which both components have inscribed into the orbit, exceeds the certain threshold, depending on the number of the marks for this night.

## 6. MEASUREMENT CORRELATION

After determination of primary orbits the measurements are correlated with the cataloged satellites. The algorithm used here essentially differ from the algorithm used for maintenance of the catalog of LEO satellites. The basic rationale are as follows.

1. The number of optical detections is by orders of magnitude lower than the number of radar detections and the number of cataloged satellites within geostationary ring is by the order of magnitude less than the number of LEO satellites.
2. The accuracy characteristics of radar and optical observations essentially differ as well. The most accurate parameter of radar observations is the range and for optical observations - the angular coordinates.
3. The character of orbital motion of GEO and LEO satellites is also different. The most unstable atmospheric perturbations, very important for the latter do not affect GEO satellites. On the other hand, the orbital maneuvers and corrections (which affect the tracking process) are performed by less than 0.5% of cataloged LEO objects compared to more than 30% of maneuvering GEO satellites.

The *first* reason allows to use for maintenance of the catalog of GEO satellites the most accurate and labour-consuming techniques. The *second* reason leads to different decision functions for the algorithms. The *third* one requires a special algorithm for GEO satellites with corrected orbits. The accuracy characteristics of radar and optical observations vary within rather extensive range thus leading to increased sophistication of the algorithm.

Different procedures are used to correlate the measurements to active or passive satellites. The reason is as follows. For time intervals significantly longer than the interval between the neighbouring measurements, a passive cataloged satellite is characterised by one orbit, obtained using all the observational data on the satellite, acquired within this interval. This orbit contains all the information required for making decisions regarding correlation of measurements to this satellite. For active satellite one orbit can not provide sufficient information. Efficient decision making for these satellites requires the knowledge of at least one orbit between the corrections and the a priori data on the character of the performed corrections (the best is the data on the time and momentum of the correction).

A priori we do not know what satellite (active or passive) has produced the measurement. Thus each measurement is subjected to correlation procedures of both types. The measurement can not be correlated to more than one satellite of each class. When a measurement is correlated to certain active and passive satellites the final decision on its assignment is the responsibility of the analyst.

### 6.1 Passive satellites

Denote the parameters of the primary determined orbit, calculated on the basis of measurement $\mathbf{x}$, as $\tilde{\lambda}_m, L_m, p_m, q_m, \tilde{h}_m, \tilde{k}_m$, their time $t_m$. The algorithm uses only one of the values, characterising the accuracy of orbital parameters - the root-mean-square deviation $\sigma_{Lm}$ of the error of determination of $L$, which is transformed into $\sigma_{Tm}$ - the root-mean-square deviation of the error of determination of orbital period $T$. Using the orbital parameters Kepler's elements $i_m, \Omega_m, T_m, e_m, \omega_m$ and the longitude of satellite projection $\lambda_m$ are calculated.

Parameters of all cataloged satellites, passive at the moment $t_m$ are propagated to the moment $t_m$ and are transformed into the same parameters as the measurement. We will denote the result $i_s, \Omega_s, T_s, e_s, \omega_s$ (we do not indicate the catalog number of the satellite for simplicity). The root-mean-square deviation of the error of determination of the orbit of cataloged satellite is denoted $\sigma_{Ts}$.

The decision function is as follows. Preliminary correlated satellites are sought for. They satisfy the conditions: $\Delta i = |i_m - i_s| < c_{ip}$, $\Delta\Omega = |\Omega_m - \Omega_s|_{mod 2\pi} < c_{\Omega p}/i_s$, $\Delta\lambda = |\lambda_m - \lambda_s|_{mod 2\pi} < c_{\lambda p}$, $\Delta T = |T_m - T_s| < c_{Tp}$, where $c_{ip}$, $c_{\Omega p}$, $c_{\lambda p}$, $c_{Tp}$ - the gates, chosen to provide low frequency of false correlations. For each of preliminary correlated satellites we calculate the functional $F = \Delta i / c_{i1} + \Delta\Omega / c_{\Omega 1} + \Delta\lambda / c_{\lambda 1}$, where $c_{i1}, c_{\Omega 1}, c_{\lambda 1}$ - are constants. The measurement is finally assigned to preliminary correlated satellite corresponding to minimal value of $F$.

### 6.2 Active satellites

The characteristic feature of the algorithm is the account of the data on the corrections for each satellite individually. Almost all active satellites perform orbital corrections to keep their longitude within certain limits (different for different objects). For some objects the direction to the satellite from certain point on the surface of the Earth is also kept within certain limits during required time intervals.

For making the decision of preliminary correlating the measurement $\mathbf{x}$ performed at $t_m$, for each cataloged satellite two orbits from the archive of orbital data are used, which timing $t_{s1}$ and $t_{s2}$ satisfy the condition $t_{s1} < t_m < t_{s2}$. The elements $i_m$, $\Omega_m$, $T_m$ and the longitude of satellite projection $\lambda_m$ are calculated using the measurement and on the basis of both archived orbits we determine parameters $i_{s1}$, $i_{s2}$, $T_{s1}$, $T_{s2}$, $\lambda_{s1}$, $\lambda_{s2}$ without propagation and parameters $\tilde{i}_{s1}$, $\tilde{i}_{s2}$, $\tilde{\Omega}_{s1}$, $\tilde{\Omega}_{s2}$ propagated to the time $t_m$.

The decision function is as follows. Preliminary correlated satellites are sought for. They satisfy the conditions: $\Delta\lambda = min(|\lambda_{s1} - \lambda_m|_{mod 2\pi}, |\lambda_{s2} - \lambda_m|_{mod 2\pi}) < c_{\lambda a}$, $\Delta\Omega = min(|\tilde{\Omega}_{s1} - \Omega_m|_{mod 2\pi}, |\tilde{\Omega}_{s2} - \Omega_m|_{mod 2\pi}) < c_{\Omega a}/i_s$, $\Delta i = min(|i_{s1} - i_m|, |i_{s2} - i_m|) < c_{ia}$, $\Delta\tilde{i} = min(|\tilde{i}_{s1} - i_m|, |\tilde{i}_{s2} - i_m|) < c_{ia}$, where the first condition for $i$ is tested only for the objects which maintain the inclination close to certain value (normally, near zero) and the second one - for active satellites, which do not maintain the inclination (for these satellites the evolution of this parameter is the same as for passive objects); $c_{\lambda a}$, $c_{ia}$, $c_{\Omega a}$, $c_{Ta}$ - the threshold values; $c_{\lambda a}$ depends on the inclination and the eccentricity, $c_{Ta}$ depends on $\sigma_{Tm}$, $\sigma_{Ts1}$, $\sigma_{Ts2}$. For each preliminary correlated satellite the functional $F$ is calculated. The final correlation of the measurements is fulfilled only when the preliminary correlation of all the measurements acquired during the considered observation session of the sensor is finished. The decision making procedure is more sophisticated than the procedure used for passive satellites. This procedure coincides with the decision function used in [7]. Regarding the procedure it is expedient to note the following.

For passive satellites a more simple procedure is used. It is efficient since the errors of orbit determination and propagation (for the moment of the observation) for passive satellites virtually always are essentially smaller than the distance between them. For active satellites the situation is different. Lack of complete information on the performed corrections leads to the errors in determination of their parameters (for the time of the observation) which are sometimes comparable or even exceed the distances between close active satellites. In this case the decision procedure for active satellites provides better quality of the decision.

For the most accomplished cases, when the "alien" satellite is closer to the measurement than the "own" one, correct decision is possible only on the basis of either the data on the time and momentum of the performed corrections or additional information. The additional information here means the "brightness curves" of the satellite, which can be acquired by some optical-electronic sensors during the observation sessions. Currently some stations already use this type of data in correlation process. Our work treats only the issues of track measurements processing. The issues of processing non-track data are beyond the scope of the work and must be subjected to special investigation.

It must be noted that sometimes the measurement is produced by active cataloged satellite but the correct correlation decision can not be achieved. In this case the measurement, as a rule, becomes uncorrelated and enters the preliminary tracking process. This is characteristic for the situations when the measurement is acquired after the performed maneuver and the data on the maneuver is lacking.

## 7. ORBIT UPDATING

The correlated measurement is recorded in the archive of data on the object: the orbit - in the archive of orbits, the marks - in the archive of marks. After that the orbital parameters of the satellite are updated. The functional minimised in the process of orbit updating is close to the functional used for updating of LEO orbits. The minimisation procedure is essentially simpler, however. the explanation is as follows. *On one hand*, for the objects in GEO the instability of the perturbations of orbital elements and the prediction errors are significantly smaller. This situation makes the problem of estimating the orbital parameters more linear and thus , more simple. *On the other hand*, the abnormalities in optical measurements are more rare than in radar measurements and thus the procedure used to reveal them can be more simple. Parameters of updated orbit minimise the functional

$$\Phi(\mathbf{a}) = \sum_{p=1}^{M}(\mathbf{x}_p - \mathbf{f}_p(\mathbf{a}))'(\mathbf{K}_p + \tilde{\mathbf{K}}_p)^{-1}(\mathbf{x}_p - \mathbf{f}_p(\mathbf{a})) + \sum_{q=1}^{N}(\mathbf{a}_q - \mathbf{a}_q(\mathbf{a}))'(\mathbf{K}_{a_q} + \tilde{\mathbf{K}}_{a_q})^{-1}(\mathbf{a}_q - \mathbf{a}_q(\mathbf{a})), \tag{2}$$

where $\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_M$ - are optical measurements with timings $t_{1m} \leq t_{2m} \leq \ldots \leq t_{Mm}$, correlated to certain object; $\mathbf{f}_p(\mathbf{a})$ - functional relationship between parameters of the observation $\mathbf{x}_p$ and parameters of the satellite $\mathbf{a}$; $(\mathbf{K}_p)_{ij} = \sigma^2_{x_{p,i}}\delta_{ij}$ ($\delta_{ij}$=0 for $i \neq j$ and $\delta_{ij}$=1 for $i = j$), $\sigma^2_{x_{p,i}}$ - mean square of the error of *i*-th component $\mathbf{x}_p$ (i,j=1,2,...,6); $(\tilde{\mathbf{K}})_{ij} = \tilde{\sigma}^2_{x_{p,i}}\delta_{ij}$, $\tilde{\sigma}^2_{x_{p,i}}$ - mean square of predicting the orbit for the time $t_{pm}$ (for parameter of *i*-th component of $\mathbf{x}_p$), i,j=1,2,...,6; $\mathbf{a}_1, \mathbf{a}_2, \ldots, \mathbf{a}_N$ - orbital parameters acquired from other sources with timing $t_{1s} \leq t_{2s} \leq, \ldots, \leq t_{Ns}$; $\mathbf{a}_q(\mathbf{a})$ - functional relationship between parameters $\mathbf{a}_q$ and satellite parameters $\mathbf{a}$; $\mathbf{K}_{a_q}$ - correlation matrix of the errors for $\mathbf{a}_q$ - structurally similar to $\mathbf{K}_p$; $\tilde{\mathbf{K}}_{a_q}$ - similar to $\tilde{\mathbf{K}}_p$; $'$ and $^{-1}$ - denote matrix transposition and inversion respectively.

Measurement's parameters vector $\mathbf{x}_p$ is a six-dimensional vector $(D_p, \alpha_p, \delta_p, \dot{D}_p, \dot{\alpha}_p, \dot{\delta}_p)$, resulting from orbit determination using the marks of the measurement. The vector $\mathbf{a}$ of orbital parameters is seven-dimensional vector $\mathbf{a} = (\tilde{\lambda}, L, p, q, \tilde{h}, \tilde{k}, s)$, where $\tilde{\lambda}, L, p, q, \tilde{h}, \tilde{k}$ - orbital elements (see section 5), $s$ - average coefficient of light pressure. Vector $\mathbf{a}$ is referred to the time $max(t_{Mm}, t_{Ns})$. The variances of the errors $\sigma^2_{x_{p,i}}$ of the components of each measurement are obtained in the process of minimisation (along with determination of the primary orbit). Certain constants pose the lower limits for the calculated values for all parameters of the measurement. The variances of errors in the components of $\mathbf{a}_q$ (diagonal elements of matrix $\mathbf{K}_{a_q}$) - are constants, chosen empirically for each data source individually. Diagonal elements of matrices $\tilde{\mathbf{K}}_p$ and $\tilde{\mathbf{K}}_{a_q}$, characterising prediction errors were also chosen experimentally. The residuals between the observed and calculated values using the updated orbit parameters for various cataloged satellites were the basis for the analysis. The result of the analysis are certain functions, chosen for all the parameters. These functions are expressed by combination of polynomials, are equal to zero for the zero propagation interval do not decrease with the increase of propagation interval. The orders of the polynomials for parameters $D, \delta, \dot{D}, \dot{\alpha}, \dot{\delta}$ do not exceed the first and for parameter $\alpha$ - the second. The time interval $\Delta t = max(t_{Mm}, t_{Ns}) - min(t_{1m}, t_{1s})$, used to retrieve the orbits of passive satellites from the archive is 150-500 days.

Prior to updating the weights of the components (coefficients of the squares of residuals in $\Phi(\mathbf{a})$) are chosen for $\mathbf{x}_p$ and $\mathbf{a}_q$ (we will call them measurements). This is fulfilled in the following way. We select the components of the "new" (not previously participated in orbit updating) measurements which have significant errors, comparing with the thresholds the *input* residuals (the residuals, obtained prior to updating, in distinction from the *output* residuals, obtained after minimisation of $\Phi(\mathbf{a})$). The weights of the selected components are nullified. The other components of the new measurements participate in the minimisation with their weights calculated using Eq.2 assuming that they are not abnormal. All the "old" (previously participated in the updating) measurements are used with the weights, obtained after previous updating, i.e. the weights of the components of the measurements, which were characterised by significant residuals during the last updating, are nullified.

After that the updating is performed. A classical differential correction technique is used for minimisation of functional Eq.2. This technique implies that one Gauss-Newton iteration must be performed in search of the minimum of Eq.2.

The obtained result is tested for reliability. The solution is considered *reliable* when at least three measurements, including at least one new have inscribed (have acceptable residuals for all parameters) into the orbit.

In case the new measurements did not describe into the generated orbit, the attempt is made to construct the updated orbit for a shorter time interval.

## 8. PLANNING OF THE OBSERVATIONS AND CALCULATION OF TARGET INDICATIONS

This algorithm has no analogy in the maintenance of LEO satellite catalog since there is no control of radar sensors emanating from the SSC. The planning of measurements is fulfilled by the analyst. The principles of planning the observations for the purposes of GEO monitoring are as follows:

1. For passive satellites with accurately determined orbit: maintenance of tracking requires 1-4 measurements per year, satisfying the requirements by SSC.
2. For passive satellites, for which the orbit is not determined accurately enough: the measurement is needed when the calculated value of the error of position determination is comparable or exceeds the maximal acceptable error of target indication.
3. For active satellites: the measurements are needed for the times when the change of the longitude of satellite projection or the orbital plane exceeds the limits, usual for the satellite. Such situations occur in case of maneuvers performed to transfer the satellite to the other orbit or to the point within GEO.

In addition the observations are planned when launches or emergency situations occur.The purposes of satellite identification using other than tracking data are also taken into account.

The plans are prepared for each sensor individually with account of the schedule of the works, conducted on the site. Planning the work of specific sensor the analyst uses the data on the informational capabilities of this sensor, in particular, operation mode (photo or optical-electronic), penetrating capability, capacity and a set of other factors, important for the work.

Selection of the satellites is fulfilled on the basis of the catalog of the objects which will reside in the field of view of the sensor during the anticipated interval of observations. This catalog is called *partial catalog*. The satellites in the partial catalog are prioritised according to the above mentioned principles. Priorities of different groups of satellites may be different for different works and therefore the analyst can choose the class of objects, interesting for particular job (for example, only active satellites with some properties or passive satellites with poor accuracy of current orbit determination).

The following types of data on the selected objects can be forwarded to optical-electronic sensor: either target indications for individual satellites or partial catalogs for certain space domains. The photo sensor receives the spatial zones, where the required (for SSC) satellites reside. The SSC may not need all the satellites within these zones. However, under the favourable conditions the sensor will acquire the measurements of all objects present in the photo plate.

Let us discuss the algorithm for calculation of target indications and partial catalogs. For passive satellites the algorithm is reduced to propagation of the parameters of the satellite and required transformation into agreed form. For active satellites the propagation is also fulfilled, but the obtained values of parameters $\tilde{\lambda}, p, q$ are replaced by the values providing that the longitude of satellite projection $\lambda$ and orbital inclination $i$ for the time of the observation $t_{ob}$ will be equal to anticipated for this satellite values $\hat{\lambda}(t_{ob})$ and $\hat{i}(t_{ob})$. The estimations $\hat{\lambda}$ and $\hat{i}$ are obtained using averaging or approximating of the archive data.

## 9. PRELIMINARY TRACKING

After the processing of measurements some of them may remain uncorrelated with the cataloged satellites. These measurements are incorporated into the catalog as new objects for which the process of preliminary tracking begins.

In the course of preliminary tracking the object is under the permanent control of the analyst. This analysis may lead to the following decisions: the object is identified with the satellite already present in the catalog; the object is considered unreliable and is removed from the catalog; the object is accepted as a new one, not cataloged previously.

In the later case satellite identification is fulfilled, i.e. its origin (international designator) must be determined. Then the preliminary tracking is finished and the satellite is transitioned to regular tracking, the basic aspects of which are described in sections 5-8. Let us consider the operations of the analyst.

1. The interactive program, calculating the approaches of the satellite to any cataloged object within certain time interval is used for identification. The principles of such program are described in [8]. The results of the calculations sometimes allow to fulfil the orbital identification for the cases of maneuvers, even when the data on the maneuver are not available.
2. When any data, received and processed by the SSC, can influence (according to the analyst) the ”destiny” of preliminary tracked satellite, the attempt to identify this object with the other ones is made. The interactive version of the measurement-satellite cor-

relation program is used. Sometimes the attempt is successful. Let us consider the typical situation. The SSC received the measurement on the satellite, which performed a maneuver. The measurement is received at the time, when the satellite is already rather far (regarding the longitude) from the point of its residence prior to the maneuver. For the moment of processing this measurement, no information on the maneuver was available for the SSC. Thus the measurement remained uncorrelated. Some time later the SSC receives the data on the maneuver. Then the repeated run of the correlation program in interactive mode leads to the required identification.

3. Target indications are forwarded to the optical sensors on preliminary tracked satellites to confirm the existence of the satellite in orbit. In case we can not manage to identify the object with the cataloged satellites but its residence in orbit is confirmed by at least two sensors, the object is considered to be a new satellite.
4. We will not treat the procedures, used for complete identification of new satellites since rather often their essence is not within the scope of orbital monitoring. We will just note that for satellite identification the non-track data of optical sensors are used as well as the data on satellite coordinates.The data from other sources of information are used also.

## 10. RESULTS OF TRIAL OPERATIONS

We will consider some of the results obtained during testing and trial operations of the described complex of the algorithms for orbital monitoring of GEO satellites.

1. *Real errors of orbit determination and propagation* are the basic characteristics, since they determine the overall performance of the catalog maintenance algorithm and the characteristics of its components. The technique used for assessment of real errors of orbit determination and prediction is as follows. For each passive satellite the residuals between its last updated orbit and all the archive orbits were calculated for the interval of 4 years. The distributions of these residuals for all passive satellites in the catalog were constructed for 15 propagation intervals $t_{pr}$ (0÷100 days, 100÷200 days etc.). The percentiles for the distributions of absolute values $k_{0.5}$, $k_{0.8}$ and $k_{0.9}$ were calculated for the levels 0.5, 0.8 and 0.9. Table 1 presents the results for the parameter $\tilde{\lambda}$. This is the upper estimation of the real errors along the track of a satellite, i.e. the maximal errors in determination of the predicted position of the object. With the increase of propagation interval this estimation approaches the estimation of real errors.

**Table 1. Predicted position errors**

| $t_{pr}$ (days) | $k_{0.5}$ (deg) | $k_{0.8}$ (deg) | $k_{0.9}$ (deg) |
|---|---|---|---|
| 0÷100 | 0.016 | 0.035 | 0.050 |
| 100÷200 | 0.015 | 0.033 | 0.047 |
| 200÷300 | 0.016 | 0.035 | 0.058 |
| 300÷400 | 0.014 | 0.031 | 0.065 |
| 400÷500 | 0.019 | 0.047 | 0.085 |
| 500÷600 | 0.038 | 0.090 | 0.17 |
| 600÷700 | 0.052 | 0.14 | 0.22 |
| 700÷800 | 0.080 | 0.18 | 0.32 |
| 800÷900 | 0.10 | 0.27 | 0.40 |
| 900÷1000 | 0.13 | 0.30 | 0.43 |
| 1000÷1100 | 0.16 | 0.39 | 0.62 |
| 1100÷1200 | 0.20 | 0.49 | 0.70 |
| 1200÷1300 | 0.22 | 0.50 | 0.75 |
| 1300÷1400 | 0.26 | 0.60 | 1.0 |
| 1400÷1500 | 0.30 | 0.70 | 1.3 |

One can see from Table 1: for prediction intervals up to 500 days the errors of position determination do not exceed 1 arc minute (12 km in linear values) for 50% of the cases; for prediction intervals up to 1500 days the errors do not exceed 0.3° (190 km) for 50% of the cases; for 80% (90%) of the cases the errors are 2-2.5 (3-4) times greater than for 50% of the cases.

2. The main characteristic of the program of *primary determination of orbits* is the share of measurements, for which the reliable orbit can be generated. Now we have achieved virtually 100% level for automatic producing reliable orbits on the basis of measurements of optical-electronic sensors. For the photo sensors this parameter is lower. The major obstacle is the presence of marks from different objects in the measurement.
3. *Correlation of measurements* with the cataloged satellites is characterised by the share of the correlated measurements. The results of data processing in recent years yield that 91% of ”satisfactory” measurements are correlated automatically and additional 7% of these measurements are correlated using autonomous work. Thus, approximately two percent of ”satisfactory” measurements become uncorrelated. The measurement is considered ”satisfactory” in case it contains not less than two marks within the interval not less than two minutes and the reliable orbit was generated on its basis. Using only this measurement it is possible to determine not less than four orbital parameters out of six with accuracy, sufficient for cataloging.

## 11. CONCLUSIONS

1. Development of the complex of algorithms for maintenance of the catalog of GEO satellites incorporated all the experience of solving this task for LEO satellites.

Thus a simple and efficient system was created.

2. The initial data, i.e. the characteristics of the sensors and the satellites determine the structure of catalog maintenance algorithms. The most important are the following distinctive features of initial data for GEO objects:

a. optical principle of data acquisition,
b. possibility to control the sensors from the SSC,
c. low average density of GEO satellites and the flux of measurements,
d. low effect of unstable perturbations on the motion of satellites,
e. significantly greater number (absolute and relative) of satellites, performing orbital maneuvers and corrections.

3. Similar to LEO region, several essential limitations for the range of observed parameters, the rate and accuracy of the observations exist for GEO satellites as well. Therefore the catalog maintenance algorithm use all available data which is stored in ”historical” archives and thus the informational losses are not too high.

4. The employed program for predicting the motion of passive satellites of GEO domain has acceptable accuracy characteristics and very high computation rate. Thus the process of tracking and detection was essentially simplified compared to similar process for LEO satellites.

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