SATELLITE IDENTIFICATION: OBJECT ORIENTED TOOLS FOR ACCURATE MAINTENANCE OF THE CATALOG

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ABSTRACT

Satellite identification procedures are based on joint analysis of orbital and non-coordinate data available in the Data Processing Center. The work presents the system of software tools used for this analysis.

The first section of the paper presents general composition of the model of the space situation used by the Data Processing Center, indicating and describing the basic entities, objects, classes, attributes and techniques (with the required databases and archives) used for statistical and logical inference. The place of satellite identification tasks in this system is outlined.

Then a set of classifiers, used for statistical inference on satellite type (spacecraft, rocket-body, fragment; specific type (series) of a spacecraft or rocket-body) is described. These classifiers use orbital and non-orbital (estimations of sizes, rotation, ballistic characteristics) data and evaluation of the evolution of these parameters if needed.

However, the actual satellite identification techniques normally involve the data on all the objects of the launch (for analysis of new satellites) and consider the structure of satellite groups and constellations –- regarding the place of the analyzed satellites in them and their evolution.

The examples of enhanced efficiency of the system compared to the simple cluster-based analysis are presented as well as the illustrations of the structural advantages and “richer” inference capabilities.

1. INTRODUCTION. MONITORING OF THE SPACE SITUATION AND SATELLITE IDENTIFICATION TASKS.

Satellite identification is one of the important parts of the process of space situation monitoring, performed by the space surveillance system. However, the formal definition of these tasks is lacking and may be is not actually needed. In fact these tasks mean the acquisition of the answers to the question *what* is the satellite, observed and tracked by the system. These answers are formulated in the framework of the general system of terms, entities and other notions established for the monitoring system. In this section we will review this system and thus will draw the scope of satellite identification tasks.

The system for the monitoring of the space situation (environment) in the broad sense is established by the spacefaring community (actually by the most active states) as an interested (affected) party. The situation when the generator of the environment (or its certain adverse aspects) becomes interested in the monitoring is quite typical.

Thus the interested party performs the primary analysis of the aspects of the situation and then establishes the system for their monitoring. After that the system is subject to permanent analysis and review to meet the changes of the requirements of the interested party and the new aspects of the monitored environment.

In the considered case of space situation monitoring the system includes the following basic components.

The *sensors*, that produce *observations*. These observations include radar measurements of satellite position and velocity, angular measurements, acquired by optical sensors, and “non-coordinate” measurements of RSCs, brightness, photometry and radar signatures.

The most important component is the *satellite situation model* integrating the physical entities and methods required for adequate representation of satellite situation to the users. This will be considered further in more detail.

Then the monitoring data (generated within satellite situation model) are used and analyzed by the interested parties applying

Procedures, closely connected with the needs and the interests of the users.

The system normally includes the observation planning and sensor targeting feedback loop to ensure efficient performance of the network as a whole.

We are mostly interested in the structure of the satellite situation model. The core of this model is the system of interacting entities and methods, providing representation of real satellite situation in the databases and reporting forms of the data processing center.

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1.1 <u>**General composition of the Satellite Situation Model**</u>

Satellite situation model comprises two major parts – the Entities, representing the "physical" objects and events that should be monitored by the system and the Methods, providing assessment of the entities (i.e. testing the reliability of their existence and evaluation of their attributes) on the basis of available observations.

The basic entities of the system are the *Satellites*, which are characterized by parameters of their orbits, descriptions of their shapes, rotation about center of masses and the general characteristics including ID, satellite type (payload, rocket-body, fragment), mission and operational status. Further we will consider the hierarchy of satellite characteristics in more detail.

The second type of the entities included in the model is the *Event-related* entities. The monitoring system must detect and characterize the following events in space: Launches, satellite Break-ups, Decays (or Deorbiting) of satellites, Maneuvers (including changes in orbital parameters and in the characteristics of shape and stability as well). Also the system must provide support to Rendez-vous operations and thus these events (and resulting satellite aggregates) should be included into the system of monitored entities as well.

The third type of the entities (objects) which monitoring is required by the users (interested civil or military organizations) are the *Mission-related* entities. First, they include satellite Constellations, i.e. groups of satellites with usually common (at the initial phase of the operational life of the Constellation) non-coordinate characteristics (shape, mass, stability) that have well-defined orbital structure, designed to ensure efficient performance with respect to criteria for certain mission.

Then normally the satellite situation model includes satellite Systems, i.e. groups of spacecraft, performing similar or connected missions residing in the orbits not necessarily constituting specially designed geometrical structure.

Other Groups of satellites can be included into this type of the entities of the model at the request of the Users or the analysts.

When the object-oriented approach is used in the design of the complex of software tools of the monitoring system these "physical' entities can be described as classes with their respective attributes. In the process of monitoring the "objects" of these classes are generated by the software (since most of the entities have rather long life and normally all the occurred events must be registered, the maintenance of respective databases comprising these entities is the indispensable condition of good performance of the system) and further data processing must ensure timely and accurate assessment of their "behavior".

The mentioned above Procedures used by (or for) the clients of the monitoring system are closely connected with the satellite situation model. However, we would like to separate them from the model to emphasize their dependence on the User's interests, additional knowledge and information, important for these procedures, but not directly necessary for the monitoring of "physical" entities.

The users (spacefaring organizations) are usually interested in two types of *Procedures* – procedures for *Situation Assessment* and procedures for *Safe Operations* support.

The first type includes (for example): the protocols for reporting on the events, techniques for evaluation of satellite constellation or system efficiency, analysis of maneuvers, analysis of the trends of the activity of certain systems or organizations and forecasting of their actions etc. Usually these analyses are performed using additional information and criteria compared to those used within the previously described Model.

The second type of Procedures includes the techniques for collision hazard assessment, collision prevention calculations and notifications (for launch and maneuver planning), analysis of the indicators of compliance with international regulations etc.

Two additional procedures, requiring intensive data exchange between the Monitoring Center and the Users should be mentioned – rendez-vous support and deorbiting operations support. These procedures assume that detailed information on the planned operation will be available to the Center, which in its turn will use the most accurate tools.

1.2 <u>**Satellite catalog, satellite identification, methods of the Model**</u>.

The major task of the Space Surveillance System is the maintenance of the Satellite catalog. Thus the Satellite is the basic entity of the model. The composition of the Satellite as an abstract entity (class) includes the following components that must be determined for the monitored satellites (objects of this class).

The first component is the orbit. In fact, for the monitoring system arrival of the satellite as an object means that its orbit is determined. Further process of evaluation of other characteristics of the satellites is based on accurate tracking of the orbits. The accepted description of satellite orbits assumes separation of certain physical types of orbits, usually LEO, geostationary orbits and high eccentricity orbits, which require different methods for motion prediction.

The next component of the description of a satellite is its shape and related size. Usually the preliminary assessment of satellite size is provided by the measurements of RSC and brightness (for optical sensors). Further the shape can be characterized using special models for description of satellite's shape as a composition of elements with certain geometry and related sizes.

The structure of the third component of the description of "physical" parameters of the satellite – stability and rotation is principally similar. We have the evaluations of "rotation coefficient" and visible period of rotation as general parameters. Then certain hypotheses (e.q. gravitational stabilization, controlled stabilization, tumbling or other types) on the type of stabilization or rotation are tested (using signature processing) and the best achievable result is determination of the true hypothesis along with the parameters connected with it (for example orientation of stability axes, precession periods, accuracy of stabilization).

Then, the common practice of the users require that the following "identification characteristics" should be determined for the satellite. First, this is International Designator, accepted by the spacefaring community as the identifier for all satellites arrived in space as result of launches from the Earth (thus the number of the launch is the "base" ID) in the course of the space era.

Then the type of the satellite (payload, rocket body, fragment) must be determined. For the payloads determination of satellite name or series, assessment (if knowledge is not available) of the mission and operational status are normally required from the monitoring system.

Thus we can see that there are two questions for which the users want to find the answers in the satellite catalog. The first question is "where?" the satellite is at certain time. Well determined orbit provides the answer to this question. The second question, as we previously mentioned is "what is it?" (see [1]). The other components of satellite description in the catalog mentioned above give the answer in the currently accepted form.

We will consider here that the satellite identification tasks are the tasks of determination of the "identification characteristics" described above. However, the scope of these tasks is not definitely determined and the understanding of the user may vary from rather simple tasks like determination of satellite type in the above mentioned sense to very sophisticated problems, for example – of determination of attitude and rotation velocity of "Mir" space station at the last period of its orbital life. Thus the analyst does not always know, whether the satellite identification task is completed.

We should mention here that the real space situation is permanently changing – launches, separations, maneuvers decays and landings occur resulting in changes in both the number of orbiting satellites and their characteristics as well. On the other hand the process of catalog maintenance on the basis of data acquired by the sensors is the process of statistical inference, having the related characteristics – accuracy of the estimation of the parameters, probability of true and false decisions. Thus the satellite catalog is subjected to permanent changes in its composition and the reliability of the assessed characteristics.

The maintenance of the catalog and related databases of the entities described above is performed using a set of Methods, designed to attain efficient evaluation of space situation.

These Methods can be divided into several classes (which can be represented as abstract classes when the object-oriented approach is used) including conceptually similar operations. Here follows brief description of the structure of these Data Fusion Classes. These classes include the following.

Preprocessors. This class includes procedures for removal of unreliable measurements and orbits – testing rather simple criteria. Then, preliminary processing of signatures include procedures for removal of distorted sections and determination of characteristic sections of radar or optical signatures. This conceptually close operation also can be attributed to this class. The involved entities will be quite different, however.

Entity Generators. This class of very important procedures will include primary orbit determination algorithms, procedures for testing hypotheses and estimating the related parameters of satellite stability and rotation (thus generating the respective elements of the description of a Satellite). Also the procedures for generation of satellite Shape and the algorithms, testing the criteria for the groups of satellites for constituting a Constellation can be included in this class.

Correlators. This class can be comprised of extensively used procedures of measurement – orbit correlation, orbit – orbit correlation and the procedures correlating sections of signatures for further processing.
Updators. The major procedures, that can be included into this class are the orbit updating on the basis of correlated measurements (differential correction) and the procedure, performing updates of rotation parameters (using processing of signature sections).
Classifiers. These are the procedures widely used for satellite identification. They include satellite type classifiers, classifiers of orbit types and satellite series. When a satellite mission is not known, the classifier of typical missions can provide its preliminary evaluation.
Characterizers. These are the procedures, designed to obtain the characteristics of certain events: decays (time, probable area of location), maneuvers, break-ups (evaluations of debris density and evolution of the debris cloud). We should note that the characterizers are used for already generated (or principally unavoidable (decay)) events.
Mergers. These are the procedures for including of certain entity into another, larger one. We can mention here satellite-constellation and satellite break-up merging procedures, the procedures for incorporating of a new signature to certain radar portrait of a satellite etc.
Finally, we must have *Supporting classes.* These should include the library of standard transformations and propagators, generators of certain reporting forms and the indispensable classes providing Data Base interface and User interface.

The aim of introducing this (or may be somewhat different or updated) set of abstract classes of data fusion procedures, which will operate with entity-objects as data is the structural simplification of the general program as a whole, since the relations between the results, required from applying certain procedures and the "life" of used entities become more transparent. Thus the user and the programmer will have the "view from above" and will better understand (even when these classes include a lot of implemented specific correlators, classifiers etc.) the scope of their own tools and operations.
Now we will proceed to more technical sections, describing the tools used for satellite identification.

2. DETERMINATION OF SATELLITE ORIGIN

Satellite origin (base ID) can be determined by means of :
-orbital identification with tracked (or previously tracked) element of the catalog;
determination of the separation of detected object from the tracked satellite;
- affiliating of the new object to in-orbit break-up;
- affiliating of the new object to certain launch.

Attempts to solve these tasks can be undertaken using either automatic data processing or manual analysis.

2.1 **Automatic techniques**

First we consider the methods and possibilities to solve the tasks using automatic data processing, i.e. without long time data acquisition, special propagation techniques and analyst's participation.

- Automatically operating *orbit-orbit correlator* is closely connected with detection (orbit generation) procedure, since for all primarily determined orbits the possibility of their correlation with known, already cataloged object (in particular with the lost one) is examined.

The statistical sense of this operation is described in [2].
When the detection-and-tracking process is efficient enough two additional tasks of origin determination can be solved within the frame of detection process. These are the tasks of identifying the separation of the new object from one of the cataloged satellites and the task of determination of the break-up of cataloged object. Both these operations again use the *orbit-orbit correlator*
The basic parameters, involved in decision making are:
t_0 – the time of additional object's arrival (time of separation or the break-up), orbital elements for this moment (the most informative are i_0 and Ω_0, characterizing the orbital plane) and the point $P_0 = (X_0, Y_0, Z_0)$ where additional object arrived.
The quality of the solution depends on how accurately these parameters can be determined on the basis of the data on the detected object.
If the object arrived rather recently and the parameters of its parent t_0, i_0, Ω_0, P_0 are well determined affiliation of the new object to the parent is usually successful since the propagation errors are small.
Thus the fact of separation of the object from the other (cataloged) one can be determined.

Detection of several objects within certain domain (time, plane, period) together with their affiliation to the same parent indicates the possibility of a break-up. The *break-up generator* will use this fact for primary generation of a Break-up entity (object)

- In practice the task of origin determination is usually solved in detection mode for the launches for which complete data on the orbits of deployed elements and the deployment scheme are available. These are usually domestic launches.

In this case the required data are introduced as hypotheses (Thus the Launch entity is generated manually) into detection procedure and the task of *Orbit Generator* is reduced to their validation using the acquired measurements.

2.2 Archives and manual techniques

The above mentioned methods for determination of satellite origin can be efficient for the cases when the tested hypotheses are not too distant in time with respect to the detected orbit. When the close hypotheses are rejected (or can not be accurately formulated) the work of the analyst and acquisition of additional data are required.

The databases on the objects and events formed on historical basis are necessary for the formulation of the hypotheses for the analysis. In this connection (and also for other tasks of space situation assessment) maintenance of the following data archives is expedient:

- Archive of orbital data
- Archive of break-ups
- Archive of dangerous approaches
- Archive of launches.

We can see [2] that the task can be solved using *Orbit-orbit Corrrelator* (2), *Orbit-launch merger (2)*, *Maneuver characterizer (2)*, where (2) means that in fact the procedures using archive data are significantly different from those, operating with the current values of parameters, solving however, similar tasks. In addition, the sense of the task will require application of Orbit-break-up merger and Close approaches characterizer.

The composition of the procedures described in [3] is very close. This fact can illustrate that when the physical sense of the of the task is adequately represented in the structure of the software, the specific data fusion procedures can be easily replaced (by more efficient or more user-friendly, for example) without structural changes.

3. INDIVIDUAL INFERENCE

In this section we will consider determination of certain “identification characteristics” of satellites which are usually required by the users and the operations of routine *Classifiers*.

3.1 Additional orbital characteristics

Since the osculating elements are the most clear for the Users, the basic types of orbits can be determined in the frame of simple model of these elements, taking into account only secular evolution.

The following “physical types” of orbits can be defined:

- equatorial ($i \approx 0$)
- circular ($e \approx 0$)
- geostationary ($i \approx 0$, $e \approx 0$, $T \approx 1$ day)
- “Molnia”-type (high-elliptical)
- corresponding to $\Delta\Omega \approx 0$ ($i \approx 90°$)
- corresponding to $\Delta\omega \approx 0$ ($i \approx 63.4°$)

Sun-synchronous orbits (providing maintenance of the local time of satellite’s passes over certain region) used for surveillance satellites also represent an important type.

In practice all the approximate equalities in the above criteria mean that respective parameters of the satellite are within certain “gates”, and this is checked by the *Classifiers*.

Normally the Users are also interested in the similarity of the orbit of certain satellite (for example, of newly detected one) and the orbits of the previously launched series of objects. This can be also determined by automatic *Classifier*. The most clear and characteristic parameters of the orbital types are i, h_a , h_p (for LEO) and the respective classifier uses the likelihood function

$$f_T = \frac{1}{N_T} \sum_{i=1}^{N_T} \mathrm{N}\left(\mathrm{Tx}_i, \sigma^2 + \sigma_i^2\right),$$

i.e. represents the satellite series as a composition of individual Gaussian peaks for the satellites of the series. (N_T - the number of satellites of series T, Tx –the values of parameters for the satellites of the series). The following likelihood function for the “new” type is used to complete the scheme

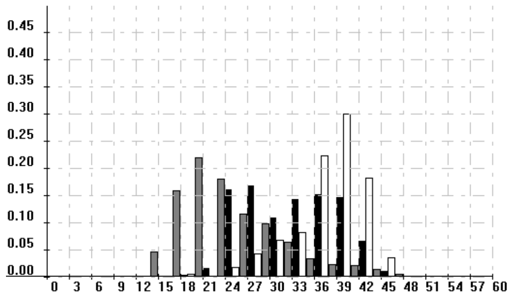
$$f_n = \frac{1}{V} \prod_{j=1}^{S} (1 - \frac{f_j}{\max f_j}),$$

where j – the index of the series, S – the number of series, V – the volume of the domain in the space of the used parameters.

The choice of this representation for the Classifier is determined by its completeness and simplicity, avoiding distortion of hypotheses, related to generalized representations.

3.2 **General non-coordinate parameters**

The generalized non-coordinate data available to the data processing center are the evaluations of RCSs (for two wavebands of the radars) and the so-called "rotation coefficient". The physical meaning of these parameters is described in [4].
These parameters can be used for two major purposes – for approximate evaluation of satellite size and in the *Classifier* of satellite type, i.e. for attributing of the satellite to one of the three categories – payload, rocket-body, fragment.
The example of the distribution of the values of RCS for three categories is presented in Fig.1
The Classifier of satellite category uses the distribution of RCSs and rotation coefficients, obtained directly from the catalog. The calculation of the weights is performed using common formulas:
Fig 1



If $z \in k$ (i.e. the value of parameter (z) enters the k-th interval of histogram *f*), the joined a'posteriori probability is determined as

$$\Pi_H = \frac{f_H^1(k)\, f_H^2(l)\, f_H^3(m)}{\sum_H f_H^1(k)\, f_H^2(l)\, f_H^3(m)},$$

where indexes 1, 2, 3 correspond to RCSs of two wavebands and the rotation coefficient and H=payload, rocket-body, fragment.

It should be mentioned that this classifier can produce good enough results for the separation of fragments from large and medium-sized payloads and rocket-bodies. Existence of small and rapidly rotating satellites require more detailed data for this classification.

3.3 Results of signature processing

The most detailed assessment of non-coordinate characteristics of the satellites can be formed on the basis of processing radar and (or) optical signatures.
The techniques for processing various types of these signals are well developed. The general review of the methods is presented, for example, in [1].
In the scope of our considerations we should note that signature processing can provide the assessment of the two basic types of satellite characteristics:

- Parameters of the Shape and Rotation of satellite about its center of mass: general sizes, sizes along the axes of satellite construction, visible (for various observation conditions) sizes, the shape of satellite body and auxiliary construction elements, types of satellite stabilization and Rotation with parameters relevant to certain hypotheses.
- The signature "portraits" – evaluations of scattering diagrams (for various types of radar and optical sensors) are important characteristics of certain satellite or series of satellites, since availability of these diagrams (accumulated in the course of observations) significantly enhances the efficiency of Shape and Rotation determination.

Usually the analysis of signature data is performed by the analyst in the interactive mode. The supporting software includes Preprocessors, Generators (of Shape and Rotation hypotheses), Updators (which use the previously determined rotation parameters and return the updated ones in case of success, or updates the satellite "portrait" in the area of newly obtained aspect angles), Correlators (of signature sections).
In some cases the available types of signature data does not ensure the domination of certain hypothesis on satellite Rotation (or affiliation to certain series) when they are processed separately. In this cases an additional Classifier will be useful, that will merge the weights of the hypotheses taking into account the informativity of currently obtained results and involved types of signature data.

4. ANALYSIS OF GROUPS

4.1 Launch analysis

If the a'priori data on performed launches are not complete, their analysis should be based on data acquired on the launched objects in the course of deployment phase, that is compared to available a'priori information (COSPAR information, launch schedules) and the Launch Archive (see. Section 2).
Preliminary separation of satellites, which can be attributed to one launch, is based on clustering in main orbital parameters i, T, Ω.

Thus the object Launch will be primarily generated. The satellites of the real launch arriving further are usually attributed to the generated entity using the same criteria.
The weights of satellite series, obtained by previously described Classifier set the priorities for the specialist analyzing the launch schemes for the observed and typical launches.
These schemes that should be presented to the analyst graphically can be formed using representation of time via orbital parameters:

$$t \approx T_0 n + \Delta T \frac{n^2}{2}$$

(where n – the number of revolutions, T_0 – orbital period, ΔT – decline of period), with further calculations of "time residuals" between the objects of the launch.
Fig 2 illustrates the technique. The horizontal axis correspond to satellite 1 (most likely – the rocket-body), the lines 0 and 2 probably correspond to two payloads and the curves 3,4,5 correspond to rapidly decaying objects, probably, launch fragments.
The technique of using such schemes proved to be rather efficient for the both cases – when the scheme is typical and can be easily recognized by the analyst (Fig. 3 illustrates the

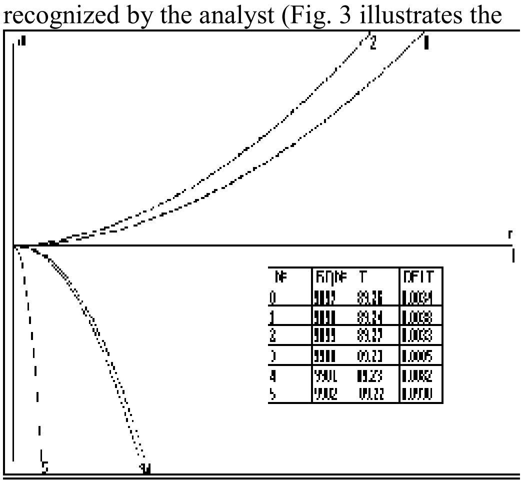
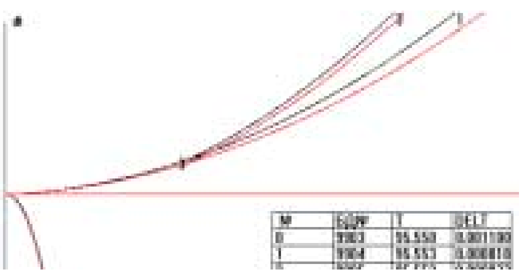


Fig.2

comparing of observed and archived launch schemes which include separation of additional satellite from the basic one) and for the case of not typical schemes as well, since the character of relative motion of satellites in the launch is rather stable.

Fig.3



It should be mentioned that the operations with the schemes are the procedures of Launch Generator, since for all the satellites of the launch their categories must be determined. Preliminary evaluation of satellite category can be based on the difference in the influence of the atmospheric drag (for altitudes lower than 500-600 km) The decline of the period for the spacecraft is usually 1.5-3 times smaller than for rocket bodies and with respect to the fragments – by the order of magnitude.

It should be mentioned, that if the group analysis is successful (for example in case of typical launch scheme) the analyst attain identification of all the objects of the launch (including small payloads which characterization using non-coordinate data is difficult enough). This provides the illustration for expediency of such analysis and archiving.

4.2 Constellation analysis

In the scope of satellite identification tasks the analysis of the constellations is used for two purposes.
First, when a new satellite arrives in space and its orbital parameters are close to the orbital parameters of the satellites of certain constellation (this can be determined even automatically using the *Orbit Series classifier* described in section 3.1) the analysis of the probable place of this satellite in the constellation can improve the understanding of the mission of the launch. The most typical analyses use the following criteria.

- Criteria of orbital structure replenishment. This is normally the case for the constellations in deployment phase, when new satellites open new orbital planes or add the new elements to the existing ones. For GEO region the enhancement of the coverage of observation or communication systems provided by the new satellite can be easily determined.
- Criteria, showing that the new satellite will soon replace one of the existing satellites of the constellation. In this cases the new objects are launched rather closely to the satellite that should be replaced. Analysis of satellite positions in the orbital planes can reveal this situation rather distinctly.
- For some constellations the Earth – tracks of the satellites are adjusted to maintain certain regime of surveying the surface of the Earth. Thus the criteria of adjusted earth tracks also give evidence to

correlated performance of the satellites in the constellation.

Other criteria for analysis of constellation efficiency with or without the analyzed satellite incorporated can be used as well when additional considerations on the constellation performance are available or suggested.

These procedures should include checks of non-coordinate parameters that will either confirm the similarity of satellite type (series) or reveal new modifications of the spacecraft.

As the result of testing these criteria the satellite (or group of satellites) can be Merged with the constellation, thus these operations constitute the essence of *Satellite-Constellation Mergers*.

Second, analysis of stability of orbital structures can be used for analysis of the operational status of the constellation and individual satellites comprising it.

The respective *Characterizers* can reveal transition of certain elements to natural evolution (especially for GEO) or the termination of the maintenance of certain orbital structures (for example triplets or pairs of satellites, maintaining in operational condition certain phasing or inter-satellite distances).

Thus we can see that the inference regarding the characteristics of newly launched satellites and the assessment of the operational status of existing ones can be more detailed when additional data on satellite constellations and groups is involved in the analysis.

Conclusions

The place of satellite identification tools in the software of Space situation monitoring system can be rather distinctly defined using the object-oriented analysis of Space situation model. The examples of tools using various types of data and operating with different entities of this model illustrate that this combination of procedures can constitute rather efficient and structurally stable software system.

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