DETERMINATION OF SATELLITE ORIGIN: WAYS TO IMPROVE THE CATALOG.

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ABSTRACT

The paper describes determination of satellite's origin as important part of catalog maintenance process.
Techniques employed to fulfill these tasks using automatic data processing are presented. Illustrative example of break-up processing is given with comparison of international designators, determined by US and Russian space surveillance systems.
Composition of data archives and related techniques of manual processing, needed to improve efficiency of decision making are suggested.

1. INTRODUCTION

Determination of the origin of satellites detected by the space surveillance network is a rather important task. Apart from general desire to perform the most comprehensive and reliable inventarization of space objects, this task is also important in the scope of space debris problems. The two major factors define its significance. The first of them is the necessity of accurate determination of debris origins. For in - orbit fragmentations and break-ups determination of responsible country and characteristics of the events are required to assess their consequences and to propose future measures. The second reason is that the knowledge of satellite origin and its type (payload. rocket body, operational or break-up fragment) allows to evaluate its potential hazard depending on the evolution of its status and orbital characteristics.
Additional reason is the obvious need to have true and identical affiliation of satellites to their origins for both (US and Russian) catalogs, used for risk assessment and environment characterization. Comparison of US and Russian satellite catalogs revealed rather significant amount of discrepancies in base international designators, indicating satellite origin (Ref. 1). More efficient cooperation in this field is needed.
In fact, determination of satellite origin (and thus the base international designator (ID)) is one of the main tasks to be solved for all objects after primary determination of their orbits. However, adequate solution of the task for different cases may require essentially variating time for acquisition of enough data - from 2-3 revolutions up to several years. Thus in practice, significant amount of satellites with uncertain origin permanently resides in the catalog. These are the objects of the "preliminary tracking stage".
Their analysis is performed continuously and the employed data and techniques essentially differ depending on hypotheses to be tested. Their scope is defined by the combination of possible causes of new objects' arrival in space and the conditions defining detection of new orbits. The practical alternatives are as follows. The sources of new objects' arrival: launch, separation (or launch from space platform), satellite break-up or deterioration. New orbits can be detected for new objects, for objects, launched previously but not observed (the case of enhancement of sensors' capabilities), for objects, previously tracked but lost (due to maneuver or lack of measurements).

Thus, the following issues are be the subject of the further sections of this paper.
General scheme of processing data on the objects of preliminary tracking stage, determination of particular tasks.
Techniques, used in operative orbits' analysis, i.e. procedures, employed to identify the launches, break-ups, orbital identification of new orbits with tracked or lost satellites .
Algorithmic principles of using historical data (archives) for affiliating new satellites to old break-ups and orbital identification for lost satellites in case of long gaps in tracking.
Principles of the analysis for launches, break-ups and other events, assuming, in particular, characterization of launch elements in absence of detailed data on deployment scheme.
It should be mentioned that the respective techniques are usually developed in the course of practice, thus some of the proposed methods are currently used and others should be considered as suggestions.

2. DETERMINATION OF SATELLITE ORIGIN AS PART OF CATALOG MAINTENANCE PROCESS

Determination of satellite origin is one of the parts of catalog maintenance process.
Real space situation is permanently changing - launches, separations, break-ups, maneuvers, decays and landings of satellites occur resulting an alterations of both the number of orbiting satellites and their characteristics as well. On the other hand the process of maintaining the catalog based on data, acquired by the sensors, is the process of statistical estimations and decisions making, having the related characteristics - accuracies of obtained parameters' estimations, probabilities of true and false decisions. In particular, one of the effects of statistical character of the problem is the possibility of false orbits arrival and the breaks of tracking (may be temporal)

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for known satellites due to lack of updating measurements. Thus the satellite catalog is subjected to permanent changes in its composition and reliability of comprising characteristics.
Efficient catalog maintenance assumes that for all orbits, comprising it, the origin is to be determined (i.e. according to international practice, the international designator of the initial launch) as well as the type of the object (payload, rocket body, fragment).
It is natural to have the composition of the satellite catalog, comprised of three main parts: the objects of the preliminary tracking stage, the objects, regularly tracked and the decayed satellites. The objects of the last part of the catalog are of interest only for retrospective analysis. Observable are the objects of the first and the second parts of the catalog.
The characteristic feature of the objects (orbits) of the first part of the catalog is that at least one of two important tasks is not solved for them: determination of orbit's reliability and (or) satellite identification (determination of satellite origin and its type).
The objects of the second part are the satellites with determined origin and type (i.e. determined ID), for which orbits regular updating is anticipated.
The "life" of the satellites in the catalog is determined by the decisions, made by automatic procedures or analysts in the course of performing the tasks, characteristic for the mentioned parts of the catalog.
The objects of the preliminary tracking stage are usually new (detected recently) though this part comprises also the orbits, which reliability is determined but determination of the origin requires long interval of orbital data acquisition. In general, the following tasks are being solved for objects of this part.
* Assessment of orbit's reliability, i.e. determination whether the orbit, determined by detection procedures, is being updated by further measurements.
First of all, the orbits are considered unreliable in case no updates occur. Final decision is made in the course of certain interval δt . Those orbits, which were not confirmed (updated or correlated to other orbits) by the end of this interval are considered unreliable. The interval δt is to be dependent on the atmospheric drag. For insignificant drag (h_P > 500km) $\delta t \sim 0.5$-1 year, for essential drag δt depends on ΔT. For example, for
$\Delta T > 0.005$ min/rev. $\delta t \sim 3$ days, for $\Delta T < 0.005$ min/rev. $\delta t \sim 10$ -15 days.
* Orbital identification of detected orbit with other orbits of the catalog (from regular or preliminary tracking parts), i.e. determination that the origin of the new orbit is in fact the old one, previously known.
* Determination of separation of the object from the other one (among the candidates for possible separation) with respective determination of the ID.
* Affiliation of the objects to break-ups (recent or old) with determination of the parent defining the ID.
* Affiliation of the objects to launches, thus defining their origin (base ID) with further determination of their type (payload, r/b, fragment).
Respectively, the following decisions can be made for these satellites.
* Determination of orbit's unreliability and resulting removal from the catalog.
* Determination of orbit's reliability, determination of the origin and type of the object and resulting transition to regular tracking.
* Making the decision of orbit's reliability and the need for further data acquisition for origin determination. In this case the object is indicated with artificial ID, denoting the date of detection.
Apart of these cases, a preliminary tracked satellite may go lost. The lost objects with previously reliable orbits remain in the catalog to retain the possibility of recovery by means of orbital correlation. The other case in fact means the first of mentioned above decisions.
The preliminary tracked object may decay. It enters the catalog of decayed objects in case its origin is determined (this is the situation for rapidly reentering r/b and launch fragments in low altitudes).
Now we will proceed to the tasks of the regular tracking stage. These tasks are not the direct subject of this paper, dealing with the issues of preliminary tracking stage, but they must be mentioned for the understanding of the general scheme of data processing and analysis.
These tasks are as follows.
* Updating and control of accuracy for all the maintained characteristics.
* Detection and assessment of orbital maneuvers and other changes of parameters.
* Prediction of reentering and determination of related parameters.
* Calculations of close approaches.
* Archiving data on satellites' parameters and their evolution.
The following decisions can be made with regard to the satellites of this part of the catalog.
* Determination of orbital maneuver or other alterations of parameters and assessment of satellite status after the maneuver.
* Determination of satellite's break-up or deterioration.
* Determination of satellite's reentering, its time and location. Transition to the catalog of decayed satellites.
* Break of tracking (the satellite goes lost). In this case the object remains in the catalog with the last updated element set in hope to its further recovery. Archiving is stopped.
We do not mention spacecraft rendezvous since these operations are not in the scope of routine activities of Space Surveillance Center.
Thus the data from both parts of the catalog is needed for successful solution of the task of satellite

origin determination. We will see further, accurate analysis requires additional databases.

2. TECHNIQUES FOR DETERMINATION OF SATELLITE ORIGIN

According to the above, satellite origin (base ID) can be determined by means of:
orbital identification with tracked (or previously tracked) element of the catalog;
determination of separation of detected object from the tracked satellite;
affiliating the new object to in-orbit break-up;
affiliating the new object to certain launch.
Attempts to solve these tasks can be made using either automatic data processing or manual analysis.

2.1 Automatic techniques

Here we consider methods and possibilities to solve the tasks using automatic data processing, i.e. without long time data acquisition, special techniques of propagation and analyst's interference.
* Automatic algorithm of orbital identification (correlation) in fact is a part of detection 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.
Statistical sense of this task is testing multi-alternative statistical hypotheses.
Decision is made using the residuals

$$\delta\alpha = \alpha_0 - \alpha_i = (\delta\alpha_i^1, \delta\alpha_i^2 \ldots \delta\alpha_i^7)$$

in orbital parameters $\alpha = (\alpha^1, \alpha^2 \ldots \alpha^7)$
compared with threshold values $\Delta\alpha = (\Delta\alpha^1, \Delta\alpha^2 \ldots \Delta\alpha^7)$ depending on parameters of the orbits, time interval between them and additional data (for example on the capability of the spacecraft to perform a maneuver).Calculation of residuals assume propagation of the orbits. Possibilities and efficiency of solving the task depends on the accuracy of these predictions. In the case when the errors are sufficiently small to ensure unique solution of the task, i. e. dominating of one of the hypotheses over other candidates for correlation, orbital identification is considered successful.
Otherwise, when either no candidates for correlation were revealed or the dominating is not ensured, the object is considered not correlated (thus, new) and further attempts to determine its origin are made with employment of additionally acquired data and manual techniques.
* In practice the task of satellite origin determination is usually solved in detection mode for launches, for which complete data on the orbits of deployed elements and deployment scheme is available. These are usually domestic launches. In this case the needed data are introduced as the hypotheses for detection procedure and it must validate them using the measurements. If the launch is proceeding according to the scheme the arriving orbits are assigned respective IDs and the objects are transferred to regular tracking. In case apriori data is insufficient for identification of launch elements of the scheme fails to be fulfilled, further analysis is performed at the preliminary tracking stage.
* When the detection-and-tracking process is generally efficient, within the scope of detection tasks two additional close tasks of origin determination can be solved. These are the tasks of identifying separation of the new object from one of cataloged satellites and the task of determination of the break-up of cataloged object.
The main 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 orbital plane) and the point
$P_0 = (X_0, Y_0, Z_0)$ where additional object arrived.
The quality of possible solution depends on the accuracy of determining these parameters on the basis of 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 propagation errors are small.
Thus the fact of object's separation from the other one can be determined. Detection of several objects within certain domain (time, plane, period) together with their affiliation to the same parent, indicates the possible break-up.
The data presented further (Table 1) illustrate enhancement of origin determination for break-up fragments in the course of the years, resulting from improvements of detection and prediction techniques.

Table 1

Sample of data on break-up processing

Int. designator	Parent name	Inclination	Event date	Nus (Dec. 96)	Nr (March 97)	n_d
72058	Landsat 1 r/b	98.3	22.05.75	50	46	9
73086	NOAA 3 r/b	102.1	28.12.73	179	143	56
74089	NOAA 4 r/b	101.7	20.08.75	131	94	31
75052	Nimbus 6 r/b	99.6	01.05.91	190	135	6
76077	NOAA 5 r/b	102.0	24.12.77	154	96	46
78026	Landsat 3 r/b	98.8	27.01.81	143	104	5
81053	Cosmos 1275	83.0	24.07.81	275	193	2
86019	Spot 1 r/b	98.7	13.11.86	57	52	2
90081	Fengyun 1-2 r/b	98.9	04.10.90	81	61	1
92093	Cosmos 2227 r/b	71.0	26-30.12.92	218	185	0
93016	Cosmos 2237 r/b	71.0	28.03.93	31	28	1
94029	Pegasus	82	03.06.96	525	212	1

The number of US cataloged fragments (N_{us}) = number of correlated with the same Russian ID + number of correlated with different Russian ID (n_d) + number of not correlated or correlated with Russian preliminary tracking stage satellites.

Nevertheless, a lot of discrepancies in international designators exist between US and Russian catalogs, especially for close orbits. It must be mentioned that the occurred break-up can result if further arrival of such discrepancies within certain orbital domain by producing affiliation of arriving new satellites to this event.

Thus, in addition to the obvious need for better cooperation between US and Russian Space Surveillance services, the necessity to use additional data and employ manual techniques is evident.

2.2 Archives and manual techniques

The above description of methods for determination of satellite origin gives evidence to the fact that automatic processing can be efficient for the cases when the tested hypotheses are not too distant in time with respect to the detected orbit. When close hypotheses are rejected (or can not be accurately formulated) the work of the analyst and acquisition of additional data are required. It is essential that the additional data is needed not only on the analyzed object . The databases for the objects and events formed on historical basis are necessary to form the needed hypotheses for analysis. In this connection (and also for other tasks of space situation assessment) it is expedient for data processing Center to possess the following data archives.

* Archive of orbital data: the elsets for all tracked satellites of the catalog (regular tracking) recorded with the rate, depending on the type of the orbit (mainly, the altitude).
* Archive of break-ups: the time and point of the event, characteristics of the parent satellite, its last orbital parameters, time of detection and the elsets for resulting fragments, their RCS and rotation coefficients.
* Archive of dangerous approaches (Ref.2): data on the approach event - time and point of minimal distance, relative velocity and approach angles, collision probability; orbital parameters, sizes and nomenclature characteristics of approaching satellites.
* Archive of launches: orbital data (generalized and recorded with certain rate for the interval of deployment), RCS, rotation coefficients, additional

non-orbital characteristics (size, shape, stability of satellites), nomenclature characteristics (ID, responsible country, launch site), characteristics of the deployment scheme. The data, stored in these archives are used in solving the tasks of origin determination using interactive (manual) mode.

2.1.1. Orbital identification, determination of separations and affiliation to old break-ups.

When the time interval $\tau = t_{det} - t_0$ from the time of new object's detection to the moment of break of tracking increases, prediction errors increase. Thus orbital identification becomes more difficult. Some of the parameters (for example the point P_0) become not informative when τ exceeds certain value. The long-term prediction errors (the main issue is to reduce the error in Ω) can be reduced only in case orbital data for the new satellite is available for sufficiently long interval. Thus the tracking of new object for rather long interval (may be several years) is needed. These orbital data are recorded in the archive and the error of long-term prediction can be reduced. The interval of new object's tracking is to be comparable with the interval during which the assumed parent was being lost.
The archived data for all the orbital parameters are approximated by part of Fourier- Taylor series according to the formula:

$$\alpha = \alpha_1 + \alpha_2 t + \alpha_3 t^2 + \beta_1 \sin \omega_1 t + \gamma_1 \cos \omega_1 t + \beta_2 \sin \omega_2 t + \gamma_2 \cos \omega_2 t + \delta_1 t \sin \omega_3 t + \varepsilon_1 t \cos \omega_3 t \quad (1)$$

where α - orbital parameter, α_1, α_2, α_3, β_1, γ_1, β_2, γ_2, δ_1, ε_1 - parameters of the model.
Using this approximation (different from proposed in Ref.3) the orbits, distant in time, can be compared.
Results of approximation can be displayed to the analyst along with graphical representation of archive data.
Similar technique can be employed to determine rather distant separations and affiliation of the objects to old break-ups.
The following points should be mentioned.
The archive of break-ups is used to form initial hypotheses of object's possible affiliation to the break-up. Also the data on the fragments is needed to find similarity between their parameters and analyzed object.
In case the object, considered to be a parent for separation had gone lost itself, hypothesis of significant maneuver should be tested. In this case data on RCS and other parameters, obtained using reflected signals are to be used.
* The archive of dangerous approaches is used to analyze possibility of collisions between cataloged objects, which can produce additional fragments. This year for the first time such a collision was rather reliably determined to occur in late July between CERISE spacecraft and the element of Ariane r/b fragmentation.

2.1.2. Launch analysis.

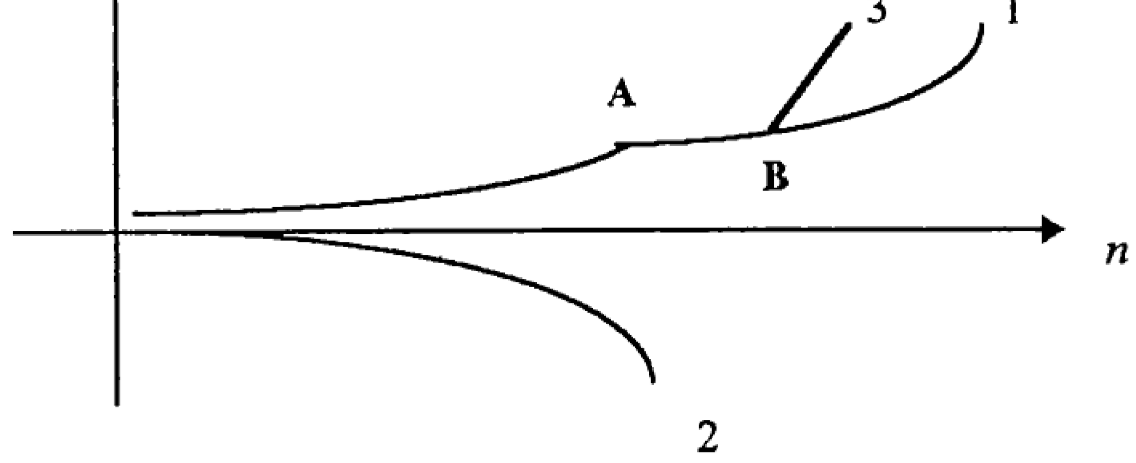
When the apriori data on fulfilled launches is not complete, their analysis is based on data. acquired on the launched objects in the course of deployment stage which is compared with available apriori information (COSPAR information, launch schedules) and the stored archives.
Preliminary separation of satellites, which can be attributed to one launch is based on clustering in main orbital parameters i, Ω, T. Thus the basic ID is normally identified for recent launches. Launch elements, arriving further are usually attributed to the launch using the same criteria.
Then primary hypotheses regarding possible types of the launch are formulated for selected objects. Their parameters are compared to the generalized data on previous launches. To calculate aposteriori probabilities the quadratic form

$$s_j^T = \sum_j \frac{(a_j - a_j^T)^2}{\sigma_{Tj}^2} \quad (2)$$

is used, where a_j (j=1,2,3) are inclination, perigee and apogee altitudes of the observed object and a_j^T are the same parameters, averaged for launches of type T,
σ^2_{Tj} characterize the spread of the respective archive data.
The errors of orbital data on the observed satellites can be neglected in this case.
The obtained aposteriori probabilities give the guidelines for further analysis of deployment schemes.
These schemes, presented to analyst graphically, are formed using the idea of representing time via orbital parameters:

$$t \approx T_0 n + \Delta T \frac{n^2}{2} \quad (3)$$

where n - is the number of revolutions, T_0 - orbital period, ΔT - decline of period;
and further calculations of "time residuals" between the objects of the launch. Fig. 1. illustrates the idea.



Here the lines 1,2,3 correspond to the objects of the launch (the horizontal axis represents certain reference orbit). The point A - the bend of the curve - corresponds to maneuver of a satellite, the point B - a new branch - indicates arrival of a new object. Significant slope of the curve 2 gives evidence to its correspondence to rapidly decaying object (usually, launch fragment).
Techniques of using such schemes, suggested and developed by L. Pylaev, proved to be rather efficient

in determination of types of the objects and their orbital performance for both cases - when the analyzed scheme is typical (and can be easily recognized by the analyst) and for new variants as well.
Preliminary rough evaluations of objects' type can be based on the difference in the influence of atmospheric drag (for altitudes lower than 500-600km). 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.

When orbital data is insufficient for determination of launch composition or the obtained assessment require additional validation, estimations of non-orbital parameters are used.
First of all the RCS or resulting efficient size d is to be used. Distributions of this parameter, characteristic for objects of different types, similar to presented in (Ref.4) are given in Table 2, provided by the same authors.

Table 2

Quantiles of emperical distributions of effective sizes' d_{ef} [m] evalutions for observed satellites

Objects' classes	distribution's quantiles for probability levels						
and their parts	0.00	0.05	0.10	0.50	0.90	0.95	1.00
all the observed satellites (100%)	0.1	0.15	0.18	0.65	2.4	3.3	17
payloads (24%)	0.15	0.5	0.6	1.1	2.7	3.4	17
rocket bodies (14%)	0.35	0.45	0.75	2.2	3.6	4.1	9
launch fragments (18%)	0.1	0.13	0.16	0.27	1.3	1.7	9
break-up fragments (45%)	0.1	0.13	0.14	0.24	0.7	1.8	12

Distributions of sizes are different for different classes. The typical size for the payloads is 1-2m with the maximum of distribution near to 1m, the typical values for rocket bodies are concentrated in two regions: 1.0-1.5m and 2-4m. The first domain contains mostly the upper stages of the US launches, the second one - of Russian launches. Near 1.7m one can see explicit minimum of the distibution for the rocket bodies. The distribution of launch fragments is essentially shifted to smaller sizes and the distribution of break-up fragments practically comprises only sizes less than 1m.

Thus these distribution can be used for classification.
In addition to these parameters the rotation coefficient can be used, which distribution are presented in (Ref.4).
Final comprehensive analysis, involving assessment of satellites shape and stability using the signatures, usually results in final decisions regarding composition of the launch.

CONCLUSIONS

The tasks of satellite origin determination are one of the main components of catalog maintenance process. The presented data gives certain evidence of improvements in solving these tasks in the course of the years. Nevertheless, further development of techniques and databases is required to attain the needed efficiency.

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