MULTI-PAYLOAD INJECTION CONCEPTION

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Abstract

Actually the cost of injection of the Payload to Low-Earth Orbit (LEO) became an important part and it has significant impact on the design of the mission strategy. One of the most efficient ways to reduce the injection cost is a multi-payload injection, i.e. the injection of a group of the spacecrafts to the one or few LEO by the same launcher.

Nowadays there is no common (unified) conception of multi-payload release. Every time, for every mission, this problem is being solved individually, without respect to the experience of previous (or parallel) solutions. That leads to considerable costs for developing, modification and testing of the GNC algorithms and on-board software with respect to requirements of customer. Evidently, that the development of the modern unified conception of multi-payload release is necessary.

This paper performs an attempt to propose a conception of multi-payload release that can be considered as an unification try.

The proposed approach is based on the decomposition of the orbital phase timeline into the closed "standard" phases – basic activities. Each basic activity contains unique maximally full set of flight operations like: rotation around of axis of Body-fixed reference frame or the main engine ignition/cutoff.

Review of feasible cases of payload assembly and its separation was performed. The quite complete list of basic activities has been designed. It includes:

- attitude pointing maneuver;
- activation of the engine for transfer to the other orbit;
- separation of the one payload (PL) or group of PL's;
- contamination/collision avoidance maneuver.

Finally, basing on the set of basic activities of flight, the multi payload release logic was developed. Assembling the basic activities of flight timeline in accordance to multi-payload release logic, we can build the orbital phase of PL pointing of any degree of complexity.

The method of additional flight timeline was developed providing flexible multi-payload release logic at the orbital phase of PL pointing. The method allows injection of any number of spacecrafts to the different LEO's assuming their feasibility by LV energetic performances.

The important point of this approach is that the assembling of the orbital phase of flight is provided by tuning of the mission data flags without change of the onboard SW source code.

1. Statement of problem

Actually the cost of Payload injection to the Low-Earth Orbit becomes an important part and it has significant impact on the design of mission strategy. One of the most efficient ways to reduce the injection cost is a multi-payload mission, i.e. the injection of a group of the spacecrafts to the one or few LEO by the same launcher.

Nowadays there is no common (unified) conception of multi-payload release. Every time, for every mission, this problem is being solved individually, without respect to the experience of previous (or parallel) solutions. That leads to considerable costs for developing, modification and testing of the GNC (Guidance, Navigation and Control systems) algorithms and on-board software with respect to requirements of customer. Evidently, that the development of the modern unified conception of multi-payload release is necessary.

This paper performs an attempt to propose a multi-payload release conception that can be considered as unification try. It allows an injection of any number of spacecrafts to different LEO's assuming their feasibility by LV energetic performances.

2. Basic principles of the conception

2.1 Feasible cases of payload's assembly and separation

Let us describe shortly the feasible cases of multi-Payload's assembly i.e. group of 2 or more spacecrafts on the one launcher. From this point of view there are following cases of mounting:

- several large-size satellites (monoblocks);
- several large-size satellites (monoblocks) and group of micro satellites.

The most attractive case by cost/functionality criterion is one or several large-size satellites and group of micro satellites.

When the mounting of the payloads is being specifies the following characteristics should be accounted:
- number and weight of payloads (PL);
- case of PL mounting on the launcher;
- separation priority.

The PL mounting is one of the most important characteristic influencing on the multi-payload injection logic. For this purpose the different adapters and dispensers are used.
The next important point is priority of the PL separation. Usually the large-size satellites are separated earlier then micro satellites. This approach is quite justified for scientific and financial points of view because the large-size satellites define the main target of the mission. If the satellites have equal priority the separation sequence is determined by the spacecrafts mounting place/geometry.

Some cases of the PL's mounting are shown in Figure 1.

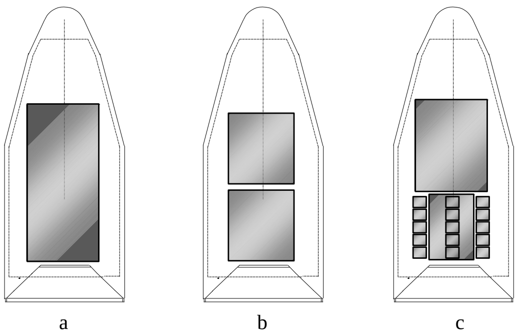

Figure 1: PL mounting cases

Generally speaking the approach, proposed in the article allows the synthesis of the separation phase for any cases of arrangement.

2.2 Main concepts of multi-payload injection

One of the most important points of the theoretical methodology design is terminology unification. It provides clear and common language to describe the main statements of the approach.

The following concepts are introduced:

Insertion phase – is a phase of flight starting from the GNC activation up to the first upper stage Main Engine (ME) cut off.

Orbital phase –	is a phase of flight starting from the first upper stage ME cut off up to the GNC de-activation.
Separation phase –	is a sub-phase of the orbital phase dedicated for the PL separation. It is activated by the “Spacecraft separation” command and completed by distancing from the released payload. This phase includes full set of maneuvers required by the PL.
Flight operation –	this term is used to define some elementary action performed in order to modify the launcher state, for example rotation around of axis of Body-fixed reference frame or the ME ignition/cut off.
Basic activity –	is a flight operation or sequence of flight operations which are unified by the common objective. Sequence of the basic activities forms full flight timeline of the orbital phase. Start and end of basic activity are determined by functional commands and labels of the Control system.
Attitude pointing maneuver –	is a flight operation changing of the launcher attitude. Maneuver could be implemented by one 3 dimensional turn or by consecutive turns around specified axes of Body-fixed reference frame.
Additional ME ignition –	is a flight operation to ignite the upper stage ME in order to supply delta velocity and to modify the orbit required by the PL or by mission evolution.
Spin –	is a flight operation that provides the rotation of the launcher around the longitudinal axis before PL separation if the rotation is required by PL.
PL separation –	is a flight operation indicating a physical process of the PL separation from the launcher. Implementation of this process depends on case of PL arrangement.
Mission scheme –	here it is a sequence of the basic activities, which provides an insertion of the PL group to the required orbits with required attitude.

2.3 Specification of the basic activities

Full set of flight operations necessary to implement for payloads injection at the orbital phase is defined by spacecraft functionality requirements. Let us reunite the separated flight operations in some logical sequence: basic activities as follow:

Attitude pointing maneuver – is applied for orientation axes of Body-fixed reference frame to the required position before PL separation. Target of that is ensuring of required orientation of launcher before PL separation. Maneuver could be implemented by one spatial turn simultaneously around three axes of Body-fixed reference frame or by consecutive turns around specified axes of Body-fixed reference frame. Required orientation is specified in reference frame associated with target orbit.

Spin before PL separation - is implemented by using low-thrust propulsion system. Spin is rotation around axis X of launcher Body-fixed reference frames with defined angular rate.

Separation of PL from the launcher – defines the process of the physical separation satellites from the launcher. It is sequence flight operations of large-size satellites or group of micro satellites separation.

Despin after PL separation – is implemented by the way of applying of sign opposite spin torque (angular rate in roll channel damping).

Contamination/collision avoidance maneuver – is performed for orientation of the launcher to the required attitude after PL separation. Target of this maneuver is to avoid the PL contamination or collision with launcher after PL separation before withdrawal of launcher from spacecraft. Maneuver could be implemented by one 3-dimensional turn simultaneously around three axes of Body-fixed reference frame or by consecutive turns around specified axes of Body-fixed reference frame. Required orientation is specified in reference frame associated with target orbit.

Withdrawal – is an additional ignition of the engine. This basic activity is applied for withdrawal of the launcher from spacecraft in order to avoid the PL contamination or collision with the launcher. ME or low-thrust propulsion could be used.

Attitude pointing maneuver before transferring to other orbit – is performed for orientation the axes of Body-fixed reference frame to the required attitude before transferring to other orbit. The target of that maneuver is ensuring of the required launcher attitude before additional ME ignition. Maneuver could be implemented by one 3-dimensional turn simultaneously around three axes of Body-fixed reference frame or by consecutive turns around specified axes of Body-fixed reference frame. Required orientation is specified in reference frame associated with target orbit.

Transferring to other orbit –is additional ignition of the engine. This basic activity is applied for transferring launcher to other orbit. For transferring could be used ME or low-thrust propulsion system.

Long coasting phase – is a phase of flight between two consequent ME ignitions. This basic activity is performed for implementation of the Homan orbit transfer. Fixed orientation (for example for telemetry stations link) or slow rotation (to avoid local heating) could be required.

Every basic activity is defined by the special commands and labels, which are generated when some functional reaches the predefined threshold. Here, it is important to note, that every basic activity could include all flight operations (attitude pointing maneuver, ME ignition etc.) required for multi-payloads injection. Finally the integration degree is determined by the reasons of clarity and logicality of orbital phase formation.

Using mentioned set of basic activities and combining them according to requirements accepted for concrete mission, it is possible to synthesize practically any orbital phase flight timeline.

2.4 Principles of orbital phase flight timeline synthesis

The synthesis of the multi-payloads injection logic is based on the next principles:

- effectiveness;
- safety;
- functionality;
- environmental safety.

Let us discuss each of them concerning the problem of multi-payloads injection.

Effectiveness is connected closely with problem of economical and technical reasonability. Evidently that multi-payloads injection will be the most widespread mode of (outer) space development. It is connected with tendency of modern spacecrafts mass and size decreasing. Therefore all researches, which have the aim to find the system solution in this field of science, have not only scientific interest but also concrete economical sense.

Safety here is ensuring of no damage of the satellites by launcher structure, ME blast, combustion gas or satellites which were separated before. Depending on case of arrangement there are few approaches, which could be used for the referred requirement implementation.
If the satellite is separated along the launcher longitudinal axis the following flight operations are performed: orientation of the launcher's longitudinal axis toward required direction before PL separation, PL release, reorientation of the launcher longitudinal axis in a safe direction after satellite separation, withdrawal of the launcher by the ME or low-thrust propulsion system. In the case of multi-payloads injection, all the set of flight operation is performed for every satellite. Such complex of activities ensures the execution of all safety requirements.
Therewith the different case of separation could be used – along the line perpendicular to long axis of the launcher. For example, it is used when group of micro-satellites is separated. That could be implemented by separation of couples of micro-satellites in an opposite direction in the same time. This approach is more attractive as for the flight algorithms complexity point of view, as for the fuel consumption. But this approach requires careful analysis of safety ensuring.

Functionality – here is a possibility to generate the flight timeline of any level of complexity by using only GNC capacity. In that statement the number of the satellites and orbits are not constrained by GNC but just by the launcher energetic capacity. The orbital phase timeline is generated by using a combination of basic activities. Then orbital phase could be tuned only by mission data. Proposed approach has considerable advantage comparing with methods which are being using widely because it allows to prepare SW for any mission by using the most simple and convenient way – changing constants of flight mission data only without changing of the on-board SW sources code.
Nowadays big attention is paid to the space debris increasing or ecological safety concerning the orbital operations. One of the important points is limitation of the space debris remaining in the orbit. Therefore de-orbiting of the launcher upper stage is mandatory for multi-payload injection.

3. Multi-payload injection logic

3.1 Multi-payload injection logic realization in the general formulation

Multipurpose system is one of the most attractive ways of launchers evolution. This system should ensure implementation of all known functionality requirements. Potential evolution of these requirements also should be forestalled. However conflicts between requirements, technical capacities and constraints have significant influence on the characteristics of the system. Development of the multi-payload injection logic and using high-performance onboard computer, which allows to implement the algorithms of high level of complexity without any damages for flight safety is one of the solution of such conflicts. In this case we are speaking about possibility of separation any number of the satellites at any (physically justified) moments of the orbital phase of flight.

Usually this problem is solved by the development of the “hard-coded” timeline for each mission. Such timeline realizes sequentially all necessary basic activities and foresees a separation of all PL at the required moments. In this case, it provides the implementation of all mission requirements. However mentioned approach has grave shortcoming – if the number of PL’s, which are separated at every orbit, is changed it is necessary to remake all the timeline in accordance with new requirements. Here we have not even spoken about changing set or sequence of basic activities. Therefore this approach could be used only for solution of the particular problems of multi-payloads injection and unacceptable for mission strategic planning.

Another approach of flight timeline generation is based on the multiple using of the “standard” legs of flight including legs of PL’s separation. Every leg consist of fixed set of basic activity and has own identifier. Generating the required sequence of the identifier, we define flight timeline according to the mission scheme. Though on evident advantages of this approach, there are some inconveniences of its using. The one of them is some uncertainty (functional commands and labels in this realization are not defined clearly), which could be a source of errors. Also the process of flight timeline logic generation is quite complex. At the phase of the mission preparation, the developers deal with fully modified onboard software. It complicates the GNC system testing process.

In consideration of all mentioned the method of additional timeline for multi-payloads logic realization has been designed. It based on idea of using two parallel independent timeline:

- main flight timeline;
- additional PL’s separation timeline.

Main timeline is divided for two phases: insertion phase and orbital phase.

Insertion phase timeline represents the set and sequence of basic activities, which are necessary for mission scheme realization on this phase. It is unified for all missions.

Orbital phase timeline includes all necessary legs of ME activation and long coasting phases of Homan’s transfer for orbit change. This timeline is generated for every mission. Taking into account different combinations of the basic activities as ME ignitions, Long Coasting phases, etc. about ten different mission schemes can be determined. Each mission scheme is labeled by unique identifier and has dedicated orbital phase timeline. The insertion phase timeline is unified for all mission schemes. The graphic interpretation of mentioned is given on the Figure 2.

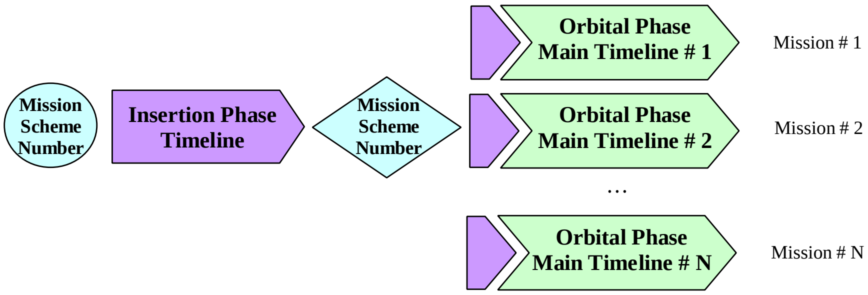

Figure 2: Main timeline identification

After every ME activation the orbital phase timeline has a set of Functional Commands to transfer to PL's separation timeline and than return back. The special parameter determines the number of PL's, which have to be separated at that moment. Scheme of the transferring realization between main and additional timelines is given on the Figure 3.

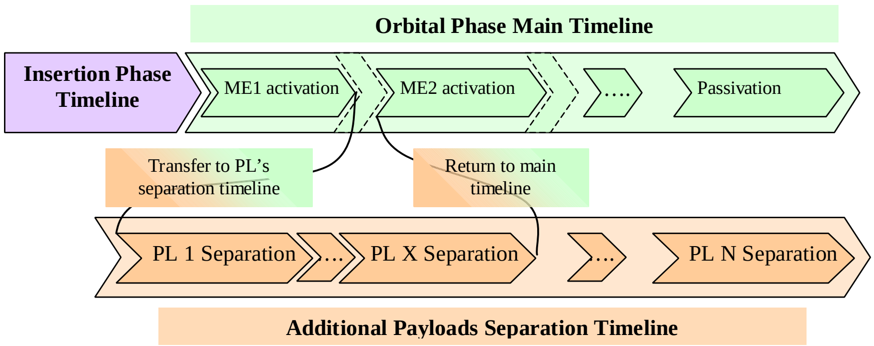

Figure 3: Scheme of the transferring realization between main and additional timelines

PL's separation timeline is an independent timeline, which performs separation of all PL's with all required set of basic activities as PL pointing, spin etc. Sequence of actions for each PL separation is specified at the mission preparation.

Proposed method of additional timeline unites the advantages of two described above approaches definiteness in the invariable phase of flight and flexibility at the orbital phase.

Multi-payload logic received thereby can be easy formalized, customized and tested.

3.2 Multi-payload logic on the orbital phase of flight

As a rule, the arranging of the orbital phase of flight is defined by the concrete launcher characteristics (the possible number of ME activations). In general case the orbital phase of flight includes following basic activities:

1. Long coasting phase before additional ME ignition.

ME ignition for transferring to other orbit is realized when required value of functional is reached. Heretofore the launcher is moving on the orbit with ME cutting off. On this leg is possible making of difference activities defined in technical requirements to the Control system, launcher or PL, e.g. star correction of navigation system or spinning in the roll channel.

2. Attitude pointing maneuver before additional ME ignition.

Before ME ignition it is necessary to implement the launcher orientation in the required direction. Parameters of the maneuver are determined basing on information about actual and required (at the moment of PL separation) orientation of launchers Body-fixed reference frames. 3 dimensional attitude pointing maneuver is more effective then consecutive from the point of view of time costs but has disadvantages from the positions of fuel economy, angular rate limitation and complexity of the realization. Often maneuvering is realized by using low-thrust propulsion system. In each concrete case decision about a type of maneuver is made basing on the information about limitations, control elements effectiveness and fuel consumption.

3. Additional ME ignition/cut off. Transferring to other orbit.

Transferring the launcher to the other orbit is implemented by ME ignition at the defined point of orbit. ME cut off is realized when required value of functional, e.g. increment of velocity, is reached.

4. Long coasting phase before deorbiting.

ME ignition for deorbiting is realized when required value of functional is reached. Heretofore the launcher is moving on the orbit with ME cutting off.

5. Attitude pointing maneuver before deorbiting.

Before ME ignition it is necessary to implement the launcher orientation in the required direction.

6. Deorbiting (additional ME ignition).

Deorbiting is implemented by ME ignition at the defined point of the orbit. ME cut off is realized when required value of functional, e.g. increment of velocity, is reached.

All mentioned basic activities include quite full set of the launcher flight operation which is necessary to realize on an orbital phase of flight.

All possible combinations of basic activities are analyzed on the preliminary design stage, in order to ensuring of realization of all possible mission schemes for concrete launcher. After that each scheme is labeled by unique identifier, which defines the structure of each main flight timeline (insertion phase and orbital phase timelines) and sequence of functional commands and labels issue, including functional commands of transferring to PL's separation timeline.

Graphic interpretation of some hypothetical orbital phase timeline is given on the Figure 4.

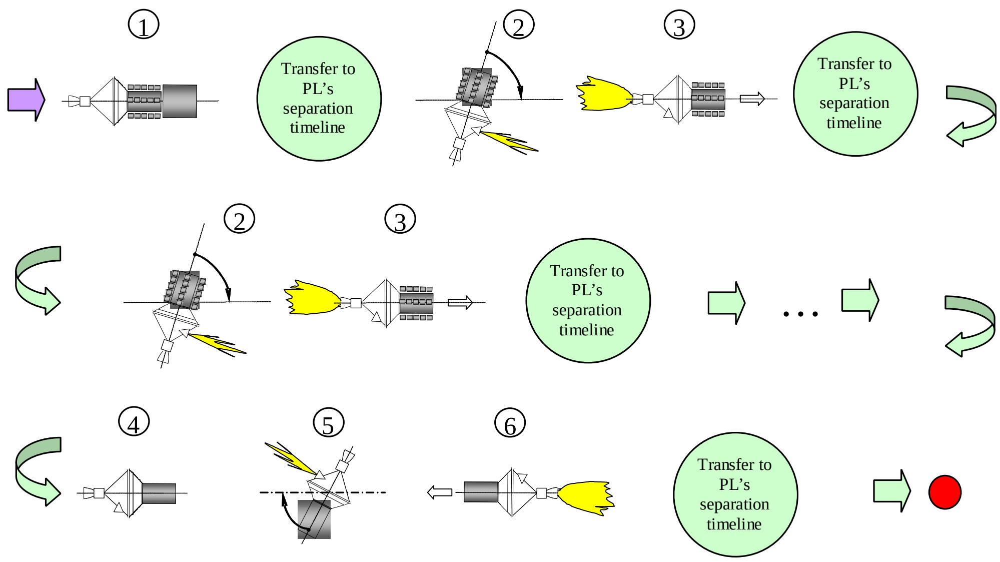

Figure 4: Orbital phase timeline

3.3 Multi-payload logic on the PL's separation phase of flight

Arranging the PL's separation phase of flight has very important meaning for ensuring of multi-payload logic flexibility. Using proposed "method of additional timeline" it is necessary to provide the possibility of realization of any sequence of PL's separation. It is obtained by the maximum saturation of the PL's separation phase timeline by the all the possible basic activities, which have physical sense. In this case the linkage of mentioned basic activities with separation of every PL is ensured. Such approach allows to ensure usability of software customization in accordance to basic principles of synthesis are accepted in Section 2.4.

Below there are some basic activities:

1. Long coasting phase (start/finish of orbital phase of flight or separation leg of one of the PL's).
ME cut off. Launcher has inserted on the required orbit. Actual attitude pointing of launcher Body-fixed reference frames (pitch, yaw and roll) is determined. If it is necessary some of the parameters (e.g. roll) could be realized by program values on the insertion phase of flight. It allows to ensure the maximum effectiveness of the next maneuvers, i. e. actual and required direction of launcher longitudinal axis are in one plane. This approach allows to decrease the fuel costs for maneuver implementation.

2. Attitude pointing maneuver before PL separation.
Main principles of the maneuver implementation are analogous to previous maneuvers.

3. Spin before PL separation.
Spin is implemented by using low-thrust propulsion system. Spin is rotation around axis X of launcher Body-fixed reference frames with defined angular rate. Why does spin is necessary? After separation, when the satellite is moving along orbit, it heats at the sunny side. The temperature drop between heated and cold sides could reach large values and it could influence on operability of the satellite. Spin, with constant angular rate, is using for avoiding that. After separation from launcher satellite is continuing rotate, it ensures acceptable temperature conditions.

4. PL separation.
Command to PL separation is issued when required conditions were reached, e.g. time moment or value of angular range. All limitations of attitude pointing and angular rate have to be implemented before separation. PL separation is implemented in accordance to mission scheme. Microsatellites separation is implemented in accordance to general rules at each command as it is necessary, e.g. in pairs in direction perpendicular to the launcher longitudinal axis.

5. Despin after PL separation.
It is not necessary to continue launcher rotation after PL separation. Spin off (angular rate in roll channel damping) is implemented by the way of applying of sign opposite spin torque. If it is necessary, the final value of roll will ensure coincidence pitch plane and next attitude pointing maneuver plane.

6. Contamination/collision avoidance maneuver.
Launcher attitude pointing is transferred in safety direction after PL separation. Often it is sign opposite to attitude pointing maneuver before PL separation. Main principles of the maneuver implementation are analogous to previous maneuvers.

7. Withdrawal.
It is implemented by the way of ME or low-thrust propulsion system ignition. The launcher is withdrawn from PL to safety distance.

Graphic interpretation of some hypothetical PL separation phase timeline is given on the Figure 5.

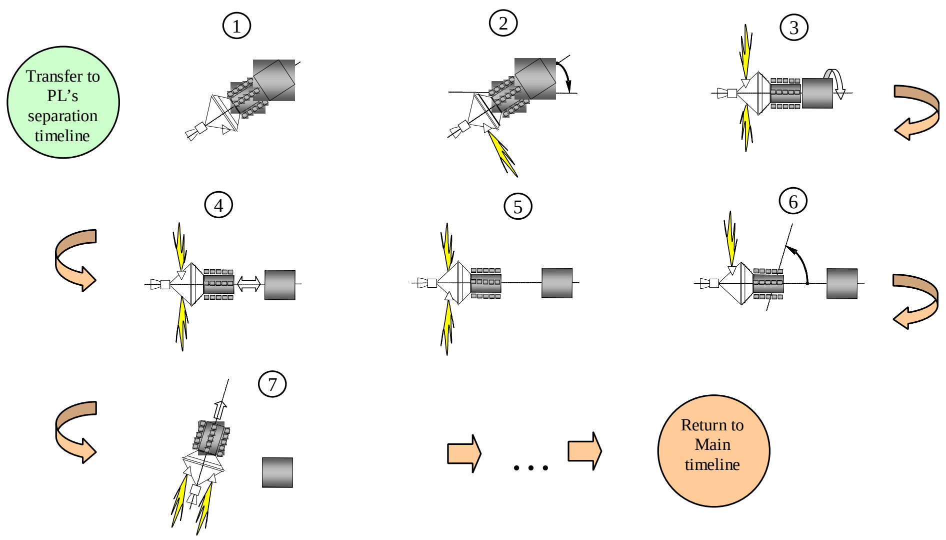

Figure 4: PL separation phase timeline

Interaction between main flight timeline and additional PL's separation timeline is provided by the following algorithm:

1. When the first target orbit was reached (first special functional command of the main flight timeline) transfer to start of PL's separation timeline is implemented.

2. All referred PL's are separated with implementation of all necessary basic activities in accordance to existing requirements for this target orbit.

3. Transfer to main flight timeline is implemented after fulfillment of all scheduled basic activities. Transfer is realized into the interval between last special functional command and next functional command of the main flight timeline according to mission scheme.

4. When the next target orbit is reached all operations repeat, with one difference – transfer to PL's separation phase timeline is implemented on the leg relevant to number of PL, which has to be separated.

Thereby the independence flight timeline from quantity of separated PL's is ensured, because in this case there are no any limitations to length of PL's separation phase timeline.

4. Conclusions

During multi-payload injection conception development, the following scientific and methodological problems were formulated and solved:

- clear interpretation of multi-payload injection logic concepts was proposed;
- set of basic activities was specified;
- main principles of flight timeline synthesis were proposed and justified;
- method of additional PL's separation timeline was designed;
- method provides transfer from the main timeline to additional one and return.

Implementation of the proposed approach allows to obtain following advantages:

- every developer of the launcher and Control system will use unified terminology;
- every developer of the launcher and Control system will use unified set of basic activities;
- process of synthesis of timeline for every existing or perspective launcher will be unified;
- developed algorithms of the Control system will be adequate to any multi-payload injection scheme.

Mentioned advantages allow to standardize the process of design in cooperation, to increase its effectiveness and to decrease time costs for coordination, correction and testing onboard software for concrete mission.