CHOICE OF A SUITABLE TARGET FOR DEVELOPING PROPOSALS FOR AN ADR FLIGHT DEMONSTRATION EXPERIMENT

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ABSTRACT

A concept for a flight demonstration experiment for active debris removal is presented. It is based on the exploitation of the launch of a payload in its desired orbit, then followed by the active debris removal demonstration experiment using the leftover resources of the upper stage, in terms of remaining propellant and electric battery residual lifetime, and a specialized piggy-back payload for the far guidance and acquisition of the selected target, the engagement and docking with it, the stabilization of the docked complex and, finally, its controlled de-orbiting. The basic components of the system will consist of a Transport and Docking Module (TDM), with its own autonomous propulsion, guidance, control and docking mechanism, and a retractable tether system, with a controllable drum for deployment and retraction, connecting the upper stage of the launcher with TDM.

Concerning the choice of the target for the active debris removal demonstration experiment, ideal candidates are represented by the Russian Kosmos-3M second stages. In fact, there are a lot of them in low Earth orbit, concentrated in two narrow inclination bands and quite evenly distributed in right ascension of the ascending node, then offering a wide range of targeting opportunities. Moreover, their simple shape and symmetry around the longitudinal axis, their known characteristics and the presence of a nozzle ideally suited for a docking with a pin probe render these abandoned stages extremely attractive from an active debris removal point of view, as also confirmed by an evaluation of their environmental criticality ranking.

1 INTRODUCTION

Despite the worldwide adoption of debris mitigation guidelines and standards, there is a growing awareness that the implementation of remediation measures might be needed in order to maintain under control the growth of debris able to jeopardize spacecraft operations in Low Earth Orbit (LEO) beyond a temporal horizon of a few decades from now. One possible and effective remediation approach might consist in the selective removal of abandoned intact objects of large mass from particularly crowded altitude and inclination regimes [1-5].

The main goal of this paper is to present a specific technical approach to Active Debris Removal (ADR), as detailed in three recent Russian patents [6-8], and the choice of a suitable target for a flight demonstration experiment.

2 TARGET SELECTION

Nearly 80% of the intact objects in orbit consist of abandoned spacecraft and rocket bodies, where most of the mass is concentrated. In LEO, they are often clustered in a relatively few and narrow altitude and inclination bands. Quite frequently, such clusters involve many nearly identical objects, like upper stages of a few basic models [9,10].

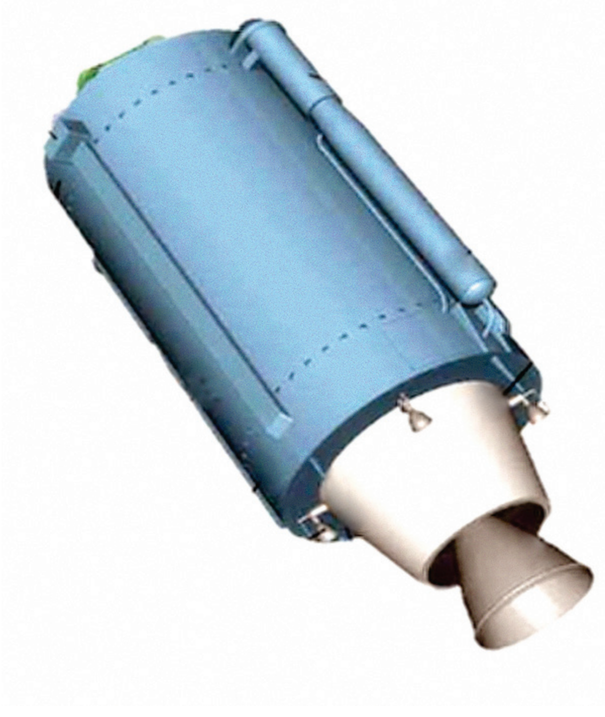

Figure 1. Schematic drawing of the Kosmos-3M second stage

Upper stages account for nearly 50% of the abandoned

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mass in LEO, and this mass is distributed in a rather small number of rocket body families. The ADR targeting of upper stages would therefore offer several advantages, in particular because targeting similar objects belonging to a few designs would make possible a number of removal missions with basically the same hardware and procedures [9,10].

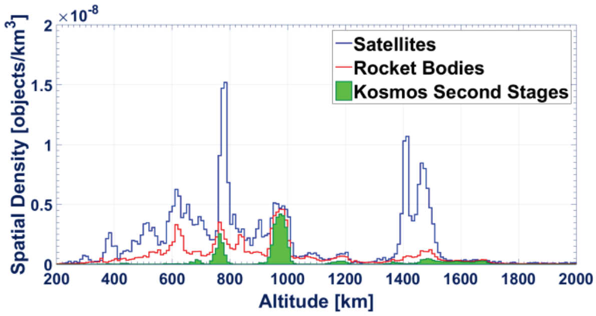

Figure 2. Spatial density of satellites, rocket bodies and Kosmos second stages in LEO

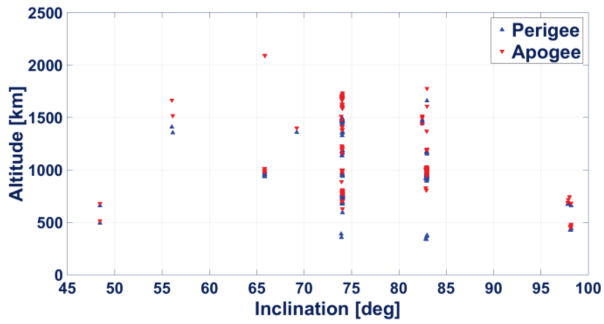

Figure 3. Distribution of perigee and apogee vs. inclination for the Kosmos second stages

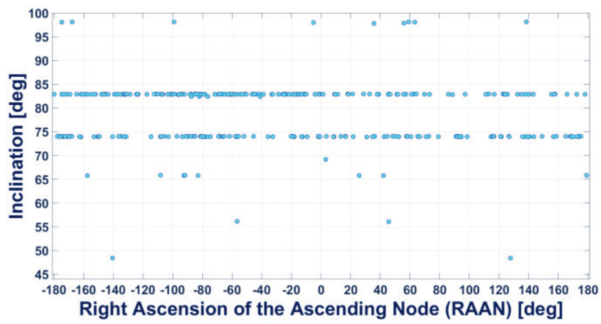

Figure 4. Relative distribution of the Right Ascension of the Ascending Node (RAAN) of the Kosmos second stages in LEO in each inclination band

An ideal target for developing ADR technologies, carrying out a flight demonstration experiment and later on performing repeated operational removals, would be represented by the Russian Kosmos-3M second stages [11,12], with a mass of about 1440 kg, a diameter of 2.4 m and a length of 6.5 m (Fig. 1). Currently, 288 of them are still in orbit, with a total mass of more than 410 metric tons, i.e. approximately 6% of the total mass of artificial objects around the Earth.

At certain altitudes, the Kosmos-3M second stages represent a substantial amount of the intact objects and the majority of the abandoned rocket bodies (Fig. 2). The greatest concentrations, around 750 and 950 km, occur well within the LEO region in which the number of orbital debris is largest. Moreover, as highlighted in Fig. 3, most of the stages are grouped only around two orbital inclinations, at 74° and 83°. This situation, coupled with a quite dense and uniform distribution in Right Ascension of the Ascending Node (RAAN), as shown in Fig. 4, would be particularly advantageous for multiple target removal missions and will not be significantly affected by the overall orbit evolution of the Kosmos second stages during the next century [10].

3 RANKING OF KOSMOS SECOND STAGES FOR ACTIVE REMOVAL

In order to assess the potential environmental criticality of the Kosmos second stages, with the goal of ranking them for active removal, the approach described in [9] and [10] was used. Taking as reference the average intact object in LEO in 2013 [13,14], with $M_0 = 934$ kg, $A_0 = 11$ m^2 and $A_0/M_0 = 0.012$ m^2/kg, placed into a sun-synchronous orbit with a mean altitude $h_0 = 800$ km and with an associated inclination $i_0 = 98.5°$, the normalized and dimensionless ranking index R_N for a generic target object of mass M and at mean altitude h was defined as follows:

$$R_N \equiv \frac{F_{cat}}{F_{0cat}} \cdot \frac{l(h)}{l(h_0)} \cdot \left(\frac{M}{M_0}\right)^{1.75} \qquad (1)$$

where F_{cat} and F_{0cat} are the fluxes of cataloged objects on the generic target object and on the reference object, respectively, and $l(h)$ is a "normalized" average lifetime function estimated for the reference object in LEO [15].

For avoiding of weighting too much the target objects with very long residual lifetimes, much longer than any reasonable temporal horizon for the current modeling and technology projections, a further condition was imposed:

$$l(h)\ /\ l(h_0) \equiv 1 \text{ when } h > h_0 \qquad (2)$$

setting a cut off at a residual lifetime of about 200 years, i.e. that of the reference object placed in the reference sun-synchronous orbit.

This normalized and dimensionless definition of the "criticality" or "ranking" index is quite easy to grasp, being R_N referred to an average (about 1-ton) intact object in LEO placed in the most popular orbital regime, the sun-synchronous one. The value found for a specific target object should therefore weight proportionally its latent detrimental effects on the debris environment compared with those of the reference body.

Applying the criticality ranking index defined by Eqs. 1 and 2 to the Kosmos-3M second stages abandoned in LEO, the results shown in Fig. 5, as a function of the mean altitude, were obtained. The highlights can be summarized as follows:

- The mean criticality ranking index was 0.86;
- The aggregate ranking index for the full Kosmos second stage family was 248;
- 200 stages were characterized by a ranking index greater than the average, i.e. > 0.86;
- 172 stages were characterized by a criticality ranking index > 1;
- 171 out of the 172 second stages with a ranking index > 1 are concentrated in two altitude-inclination bands (745-780 km with inclination ≈ 74°, and 920-985 km with inclination ≈ 83°);
- Also 193 out of 200 stages with a ranking index > 0.86 are concentrated in two altitude-inclination bands (740-780 km with inclination ≈ 74°, and 920-1000 km with inclination ≈ 83°).

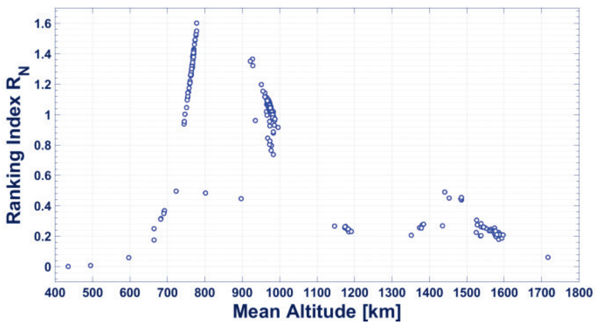

Figure 5. Environmental criticality ranking of the Kosmos second stages in LEO compared with a 1-ton abandoned object in sun-synchronous orbit at 800 km

The analysis carried out then confirmed that the Kosmos-3M second stages might be a very good target for experiencing active debris removal technologies, and also for carrying out efficient operational large-scale removals in a couple of altitude-inclination bands.

4 FLIGHT DEMONSTRATION EXPERIMENT CONCEPT

The proposed concept for a Flight Demonstration Experiment (FDE) consists in using the associated launch of a Space Launch Vehicle (SLV) for placing a payload into the desired orbit, then followed by a FDE for active debris removal. As possible targets for the ADR mission, Spent Rocket Bodies (SRB) are considered, in particular the second stages of the "Kosmos-3M" launch vehicle.

The composition of the SLV for the flight demonstration experiment will include a launch vehicle and an upper stage. The payload will be fist delivered into the desired orbit, and the remaining energy resources will be used for the ADR demonstration experiment. One of the most important requirements for the mission success will be the choice of the appropriate target among a plurality of SRB already in orbit [6-8]. The selection will be made taking into account the performances of all the constituent elements involved in the proposed system.

The flight demonstration experiment will include the following phases:

1. Far guidance of the Upper Stage (US) and Transport and Docking Module (TDM) into the region of space where the target resides;
2. Separation of TDM from US by a tethering rope (Fig. 6);
3. Close guidance of TDM to the selected target stage (SRB) (Fig. 7);
4. Docking and capture of the selected target stage (Fig. 8);
5. Stabilization of the complex [TDM+SRB], using the propulsion system of TDM (Fig. 8);
6. Retraction of the tether and formation of the docked complex [US+TDM+SRB] (Fig. 9);
7. Active removal of the complex [US+TDM+SRB] using the US and TDM propulsion systems (Fig. 9).

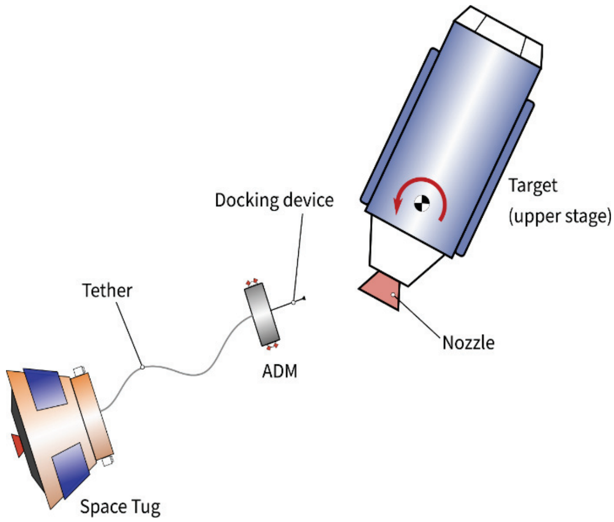

Figure 6. Separation of the docking module (ADM) from the upper stage (Space Tug) by a tethering rope, towards the target (spent upper stage)

Concerning the restrictions on the choice of the ADR target – a spent second stage of the Kosmos-3M launcher – as a rule, almost all of them have random angular velocities relative to the center of mass, i.e. their kinetic moments are different from zero. To cancel them, the propulsion system of TDM after docking with the target is proposed (Fig. 8). Consequently, the design parameters of TDM impose a restriction on the possible dynamic characteristics of the potential target [6-8].

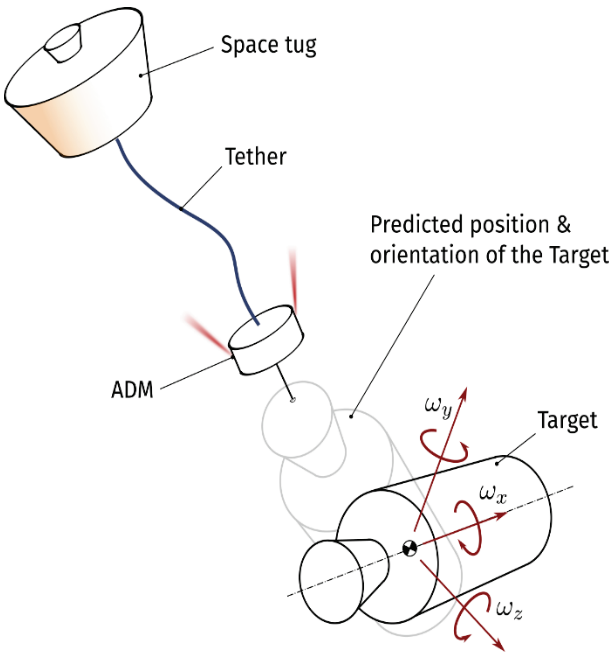

Figure 7. Having estimated the attitude motion of the spent rocket body (SRB), the transport docking module (TDM) corrects its relative motion, waiting for the appropriate time for docking when, as a result of the SRB rotation, the nozzle of the SRB passes near the capture probe

After the formation of the docked complex [US+TDM+SRB] (Fig. 9), the de-orbiting maneuvers are carried out by means of the US propulsion system; accordingly, provision of controllability, stability and quality stabilization process will be determined by the moment-centering characteristics of the bundle with respect to the US guidance and control capabilities. Another problem will be represented by the possible tendency to explode of the potential targets due to the presence in the tanks of residues of fuel unused for a long time. Moreover, the active functioning of the existing US in orbit is limited due to the capacity of the electric battery. Therefore, the total duration of the period of time available to carry out all the events (orbit insertion, far and near guidance, docking and capturing, transition to descent orbit) should not exceed a given length. The general criterion for the selection of all systems involved (launch vehicle, upper stage, payload, TDM, and SRB), within the rocket-space complex, will be to guarantee a sufficiently high probability of success for the flight demonstration experiment.

5 TARGET CHOICE CRITERIA

The choice of an appropriate ADR target in LEO for a flight demonstration experiment is a multi-criteria problem. The most relevant criteria for the experiment concept described in the previous section are the following:

- The characteristics of the primary mission payload (mass, dimensions, deployment orbit);
- The characteristics of the launch vehicle and the upper stage;
- The size and mass of the ADR target, and its risk of collision with other space objects;

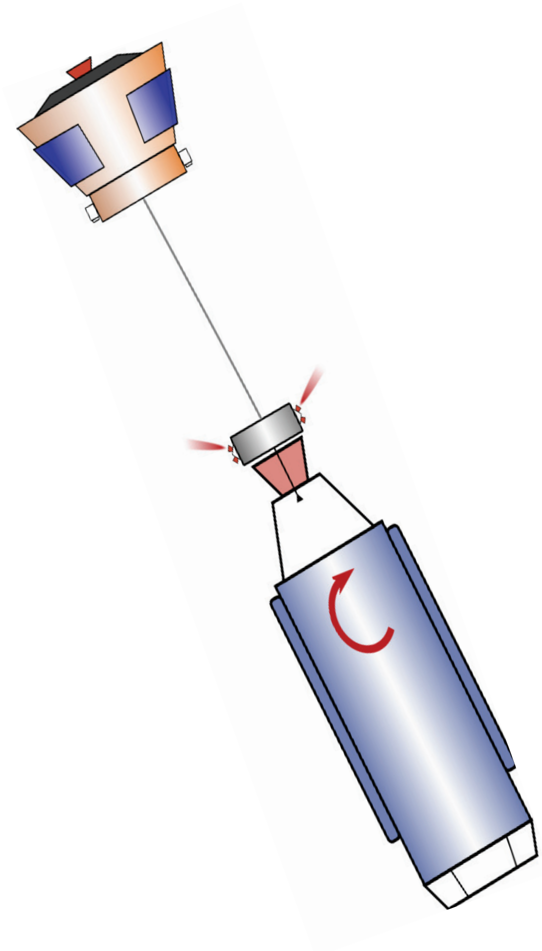

Figure 8. Docking with the target using a probe-cone mechanism, being the nozzle of the target stage the "cone", and de-tumbling of the rocket body

- The presence of liquid fuel residues in the tanks of the spent target stage, and their presence in the illuminated portion of the orbit, making them the most explosive;
- The fuel remaining in the tanks of the upper stage of the space launcher after the deployment of the primary payload, from which the achievability the target orbit and the opportunity for ADR depends;

- The accuracy of target designation and the illumination conditions in orbit during the phases of near guidance and docking;
- The kinetic moments of the spent stage and the possibility of docking based on the proposed technologies;
- The possibility of annulling the kinetic momentum of the complex [TDM+SRB] (Fig. 8) using the TDM propulsion system;
- The ability to create the complex [US+TDM+SRB] (Fig. 9), reorienting and de-orbiting it;
- The overall probability of success of the complex events listed above.

6 FDE CONCEPT DETAILS

Choosing a space launch vehicle and an upper stage for the flight demonstration experiment will be based on system analysis, which will include the selection of specific objects from a variety of existing ones:

- Space launch vehicles and upper stages from a finite set {SLV, US} with performance characteristics that ensure the launch of the payload (space craft) and the FDE mission;
- A space craft (SC) - payload (operational orbit, mass and dimensions) from a finite set {SC}, included in the scheduled launches;
- A target (SRB) in the range of possibilities {M};
- A FDE with planning and design parameters {X}, ensuring the implementation of the proposed concept.

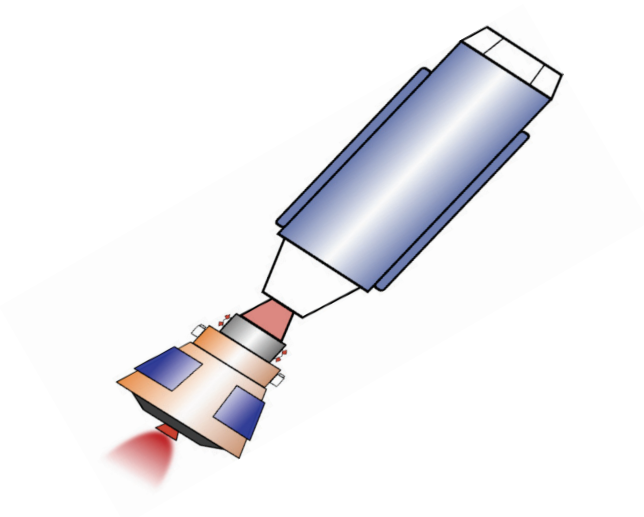

Figure 9. Retraction of the tether, docking with the upper stage, reorientation maneuvers and de-orbiting, completing the ADR mission

Considering the total payload of the space launch vehicle plus upper stage combination, i.e. [SC+TDM], the energy capabilities of SLV and US should be adequate to:

- Launch a given SC into the desired orbit;
- Implement the long maneuvers aiming to target rendezvous using the US remaining energy after the SC separation;
- Dock the target spent rocket stage (SRB) and create the [US+TDM+SRB] complex using the TDM propulsion and the residual energy of US;
- Carry out the ADR de-orbit maneuver of the [US+TDM+SRB] complex, aiming at a safe pre-determined area of the surface of the Earth, using the residual energy of US.

The active functioning of the existing upper stages in orbit would be limited, due to the available capacity of the electric batteries. Therefore, the limiting operation time T_{US} of an upper stage of potential use for an ADR flight demonstration experiment should be greater than the total duration of the period of time T_{Σ} needed to carry out all the events, i.e.:

$$T_{US} > T_{\Sigma} = T_{SC} + T_I + T_N + T_D + T_A \tag{3}$$

where T_{SC} is the time needed to deploy the SC into the desired orbit, T_I and T_N are the times needed for long-range maneuvers and near guidance to the target stage, respectively, T_D is the time needed for docking TDM with the target stage, de-tumbling the [TDM+SRB] complex and forming the docked [US+TDM+SRB] complex, and T_A is the time needed for completing the ADR de-orbit maneuver of the [US+TDM+SRB] complex.

The upper stage limiting operation time T_{US} is a strong constraint and leads to a significant reduction of the possible orbits and mass both for the payload and the target. The choice of the primary payload from the scheduled launches will be therefore based on the relative proximity of the requested deployment orbit to that of the intended target, for example being preferably coplanar. In any case, after the payload deployment, the residual energy resources of the upper stage, i.e. propellant and electrical power, must be sufficient for the flight demonstration experiment, while satisfying Eq. 3.

7 TDM DESIGN PARAMETERS

The main TDM tasks will include: the separation from the upper stage on a tethering rope, near guidance and docking with the target spent stage SRB, using the “pin-cone” system, the dissipation of the angular momentum of the [TDM+SRB] complex, and the connection between the upper stage and the target spent stage through the tether system.

The tether system, including in its structure a controlled tether drum, will be placed on the upper stage. Working both in unrolling and rolling mode, the tether will have a length of up to 2 km.

In accordance with the tasks assigned to TDM, the main design parameters are:

- The jet thrust magnitude of each stabilization channel;
- The number of engines;
- The type and stocks of liquid propellant for the jet engines and the electricity stocks;
- The length of the tether, the speed of deployment and the tension during its retraction;
- The distance at which starting the near guidance phase;
- The configuration of the "pin-cone" capture and docking equipment and the detection of a good lock in the target frame;
- The separation and docking systems installed both on the upper stage and on TDM.

8 FUTURE WORK

In conclusion, the proposed concept might represent an affordable and sound approach to the task of removing efficiently from low Earth orbit a significant amount of abandoned mass, in particular from regions of space already crowded by space debris. However, several important issues remain to be solved before a demonstration flight experiment might be accomplished.

The researches carried out so far allowed the identification of the major challenges for future work. They are the following:

1. Carrying out mathematical modeling of all mission phases, starting with the choice of the cosmodrome, the type of space launch vehicle, upper stage and payload (its mass and injection orbit), and of the amount of residual propellants left in the tanks of the upper stage to accomplish the flight demonstration experiment;
2. Definition of the main element of the proposed flight demonstration experiment, i.e. TDM, characterized by its design and structural characteristics. The selection of the characteristics of the TDM Cartesian propulsion are determined by the conditions of having two consecutive zero kinetic moments of the following systems:
   a. docked aggregate TDM+SRB;
   b. tethered system: US + tether + docked aggregate TDM+SRB.

   The first kinetic moment is due to the tumbling of the SRB, while the second kinetic moment is caused by the different velocity of the centers of the mass of the US and the aggregate TDM+SRB;
3. Study of the dynamics of the motion of the docking probe within the inner surface of the rocket engine nozzle, taking into account the elasticity of the probe and the SRB tumbling;
4. Development of a control algorithm providing collinear longitudinal axes of TDM and the SRB at the time of the beginning of the introduction of the probe's pin into the engine nozzle;
5. Development of control algorithms for the propulsion systems of US and TDM, and for the tether system drum during the stage of tightening US and the complex TDM+SRB;
6. Need to develop appropriate schemes and control algorithms to deal with the constraints of the US propulsion systems on the amount of control moments along the axes of stabilization. In fact, these limitations lead to the situation that, in order to complete the ADR mission, the additional use of the TDM propulsion system is necessary for orientation and de-orbiting of the docked complex (Fig. 9).

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