Deployment of the tethered satellite system (TSS): Numerical modeling and dynamic control

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Abstract

Tethered satellite systems (TSS) can be needed to carry out many specific orbital experiments and maneuvers in present time, and in the future to build a big space complexes which extend from tens to hundreds kilometers. In the periphery of these huge constructions there will be a micro gravity that facilitates the long stay of people in space [1]. To provide the rigidity of tether orbital constructions, it is necessary to create certain force of tension in tethered elements by means of gravitational, centrifugal, and possibly by electromagnetic forces. It makes sense using micro-jet engines to provide a short-term tension in tethers during their deployment.

It is possible to consider so-called «gravitational dipole» (G-Dipole or GD, see [2]) as the basic building tethered element. This element is a long gravity-gradient stabilized (along the local vertical) tether which connects base-satellite and sub-satellite. In spite of some carried out rather successful deploying experiments, such as TSS-1 (1992), SEDS-1 (1993), SEDS-2 (1994), TSS-1R (1996), YES2 (2007), orbital deployment of large GD remains the uneasy technical problem. Analytical solution of system of dynamic equations containing ordinary and partial derivatives for G-Dipole systems with variable length of tether, is also the extreme challenge. Authors offer the peculiar multi-functional discrete model describing deployment and dynamics of single GD by numerical modeling.

Linearized dynamic equations of a body moving in orbit plane, in the local coordinate frame XY attached to basic module and rotating with angular speed ω, are:

$$\begin{aligned} &\ddot{x} - 2\omega\dot{y} = 0 \\ &\ddot{y} + 2\omega\dot{x} - 3\omega^2 y = 0 \end{aligned} \quad . \tag{1}$$

These equations, when body is being thrown from coordinate origin of local coordinate frame, and its initial speed vector V_0 is directed at angle θ relatively local vertical Y, have the solution:

$$\begin{aligned} x(t) &= (3t - \frac{4}{\omega}\sin\omega t)V_0\sin\theta + \frac{2}{\omega}(1-\cos\omega t)V_0\cos\theta \\ y(t) &= \frac{2}{\omega}(1-\cos\omega t)V_0\sin\theta + \frac{1}{\omega}\sin\omega t V_0\cos\theta \end{aligned} \quad . \tag{2}$$

Studying analytically local trajectories (2), one can find an angle providing the maximum distance L_{max} of body's throwing along local vertical Y: $\theta_m = 133.607^\circ$, see Fig. 1. In case of weakly stretched tether with the end sub-satellite, numerical model of its dynamics and expansion gives ballistic trajectory which is very similar to (2).

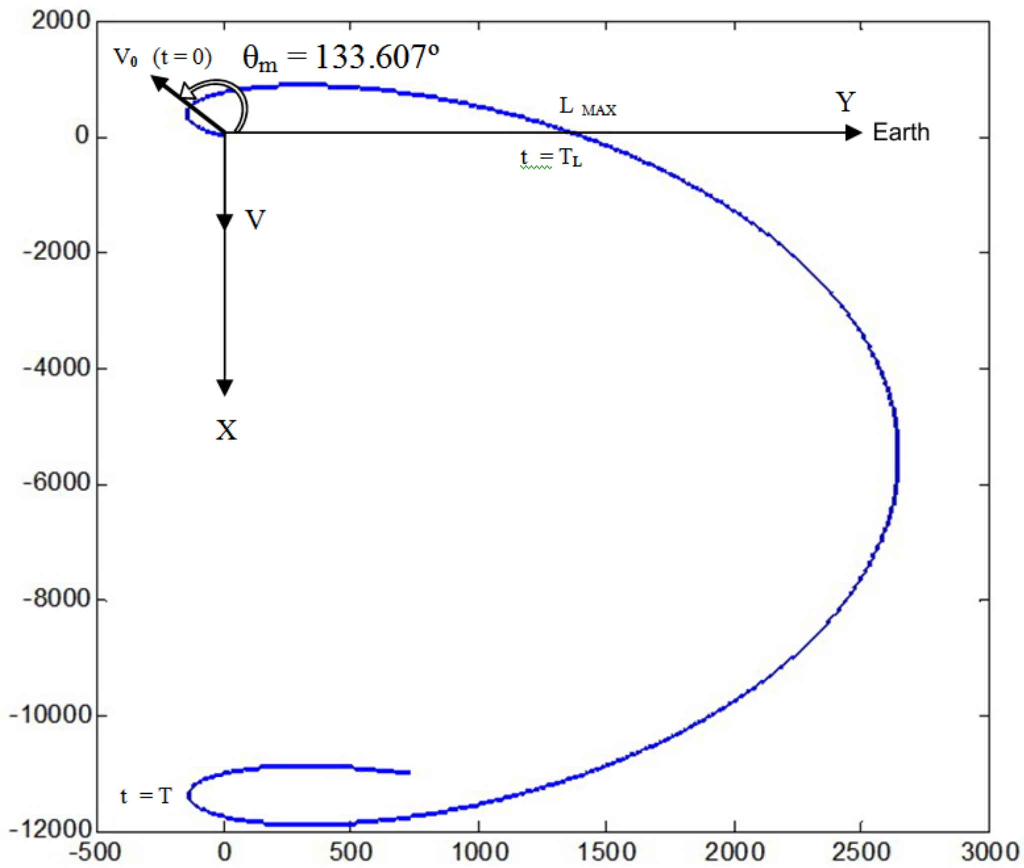

Figure 1. Optimal relative trajectory providing the maximum distance along vertical Y.

Discrete model of a long tether contains specially developed discrete final element L_0, which has angular and linear stiffness in the joints of its three rigid segments. This element has 12 degrees of freedom, represents deformations of a stretching, torsion and bending, and provides good accuracy even at big displacements. Not only the gravitational and inertia forces are taking into account, but also forces of resistance of atmosphere acting on its segments, as well as on the end GD modules. The whole model of G-dipole is a chain of N rigid bodies (see Fig. 2), and it allows to describe dynamics of a tether both at fixed tether's length and during its expansion with end-mass payload. Dynamic equations of model are written in FORTRAN-90 codes, and they include, besides mentioned forces, the viscous damping in model's joints and thrust force of sub-satellite acting in the coarse of expansion and stopping of a tether. Equations also include the decelerating friction force acting in extract unit positioned on the base-satellite.

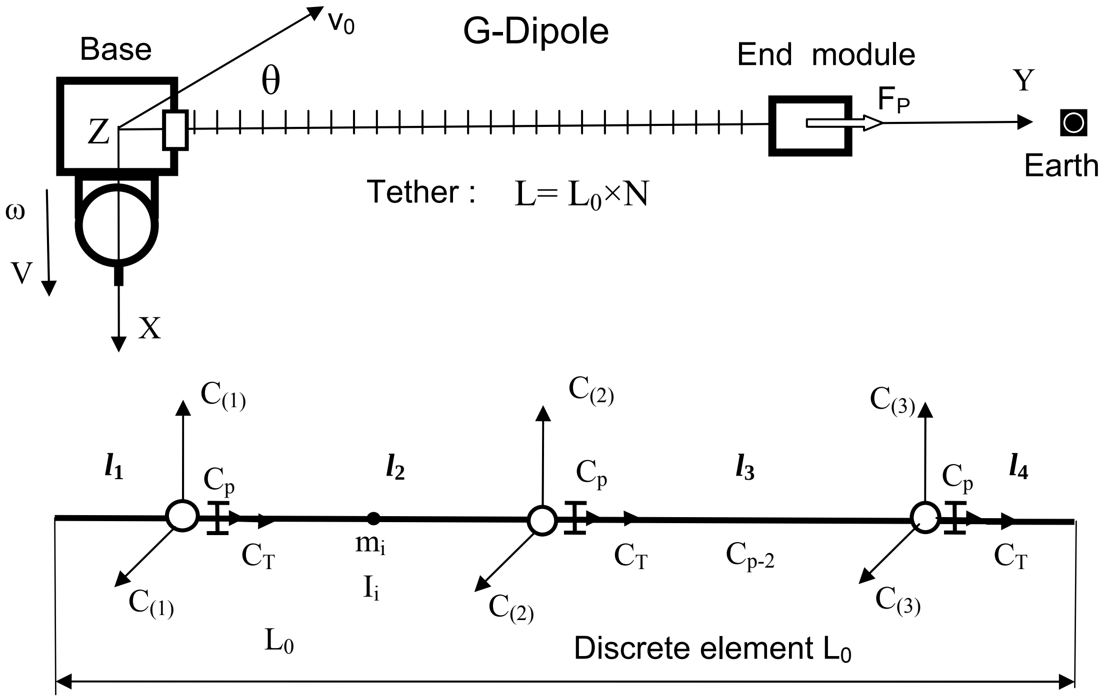

Figure 2. Discrete model of G-Dipole tethered satellite system.

Authors of model carried out a considerable quantity of computer simulations which allowed finding the desirable smooth mode of GD expansion and a way of tether's stabilization near the final configuration.

For visualization of data at various modes of GD deployment and dynamics, it is necessary to view whole process in the course of time. For this purpose, special program was written in FORTRAN-90 codes, using graphic library OpenGL of Windows operational system. Visual window of this program is shown in Fig. 3. The value of time point, a tether's configuration, value of stretching force in the tether, an emission angle θ, as well as inertial and geometrical parameters of all system are displayed in this window.

For regular deployment of G-dipole, it is necessary to find such dynamic-control mode of emission and stabilization of tether with sub-satellite along local vertical, which does not allow of tether's entanglement and provides its stopping near the final configuration. Such desirable smooth mode of reaching sub-satellite's end position with tether's stabilization along local vertical by guide control of sub-satellite thrust vector, was found. In the model, thrust force acts during stopping process and remains constant in magnitude, changing only an inclination angle θ relatively local vertical Y. For example, suitable «AUTO-Θ» braking law has the form:

$$\theta_A = 45^\circ \frac{D_X}{D_{X0}} sign(V_X)\,. \tag{3}$$

Here V_X - is projection of the velocity of sub-satellite onto axis X; D_X - current distance to the local vertical Y, D_{X0} - its value when braking thrust is turning on.

Numerical experiments had demonstrated high efficiency of the law (3): sub-satellite and tether were stopping quickly, without undesirable fluctuations of the tether.

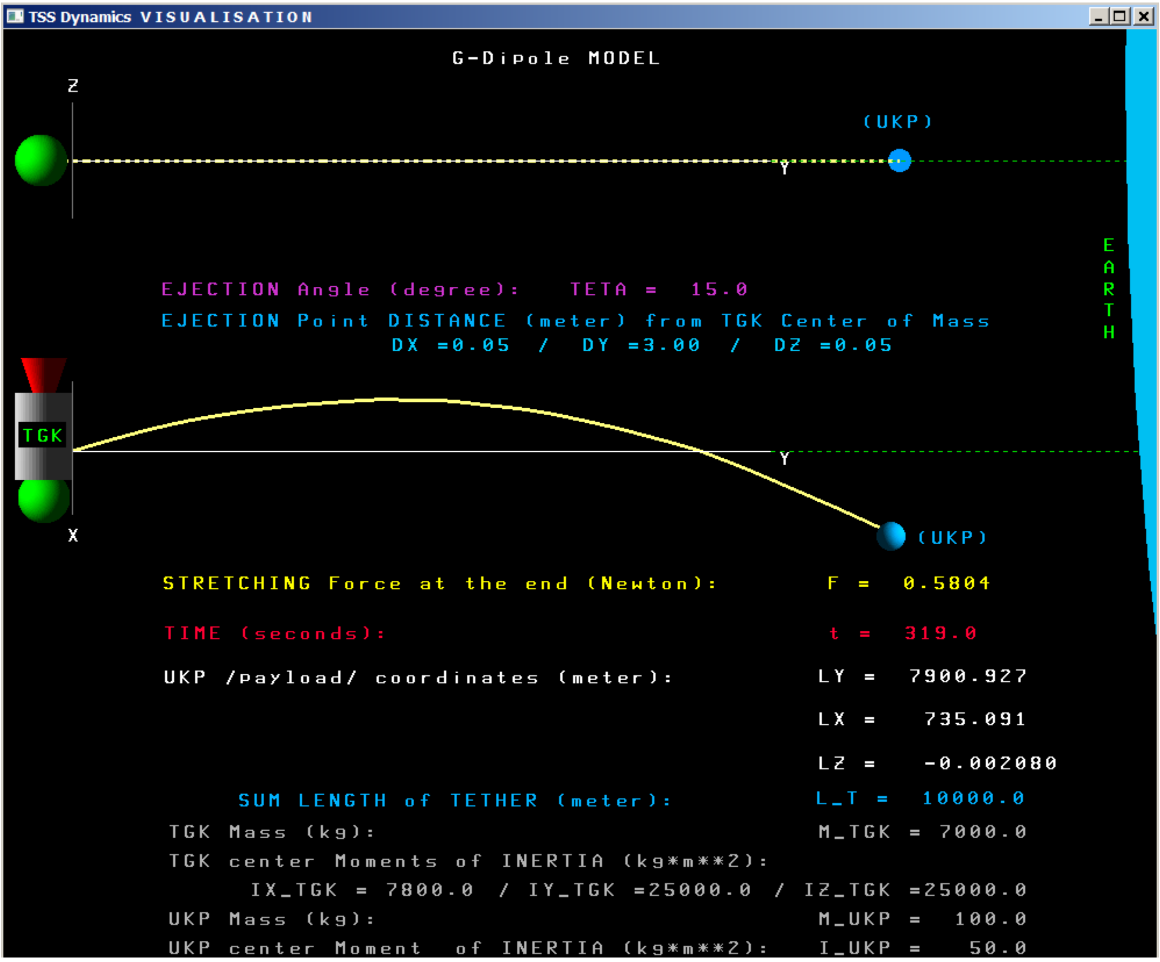

Figure 3. Visualization of G-Dipole deployment (screenshot).

According to computer simulations, developed discrete model showed high speed of computation and the good accuracy in GD dynamics. Using this model, it was possible to find the smooth mode of G-dipole deployment. Besides, model allows studying many other modes of GD dynamics, which can not be investigated in experiments at the earth-terrestrial conditions.

References

[1] Beletsky V.V. and Levin E.M. Dynamics of space tethered systems. 1990. Moscow, Nauka. 336 p. (In Russian).

[2] Smolnikov B.A. and Leontyev V.A. Evolutionary dynamics of orbital objects. 4^{TH} European Conference for Aerospace Sciences (EUCASS 2011), Saint Petersburg, Russia, 4-8 July 2011. EUCASS CD book of papers 2011, Symposium 4, № 24, 4 p.