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Tether-Assisted Disposal of Inoperative Satelleites

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Abstract

Two methods using long tethers are examined for the disposal of inoperative satellites or debris in geostationary orbit (GEO). The disposal method is to move the orbit of the satellite 300 km from GEO to prevent interference with operating satellites. The first method uses a service vehicle with dual 300km tethers. The vehicle docks with target number 1, then uses rocket thrust to carry the pair to target number 2. The two satellites are extended upward and downward 300 km by the two tethers and are released in turn. After the first release, the service vehicle drifts to the next target, releases the second satellite, then uses a small rocket thrust to rendezvous with target number 3. The second method is to oscillate a single target satellite upward on the end of a 600-km tether into an in-plane pendulum mode with a libration half-angle of 15 degrees. The satellite is released on the backs wing, removing some energy but maintaining perigee 300km above GEO. The service vehicle gains energy, returning nearly to GEO after it retracts the tether. Tether-based disposal is compared in terms of mass required with conventional rockets and with the tumble-orbit transfer, previously proposed by one of the authors. Tethers offer some advantages over rockets for the relatively low delta-v required (about 5 m/s per operation).

1. Introduction

The geostationary orbit (GEO) now contains a multiplicity of communication satellites, and several new ones are being launched each year. As these satellites reach the ends of their operational lives, they must be disposed of to prevent clutter in GEO and to reduce the hazard of collision. Debris from collisions in GEO will not decay from orbit due to atmospheric friction, and will therefore present a permanent collision hazard for future spacecraft. Many GEO satellites are designed to boost themselves 300 km above GEO at the ends of their lives, using two firings of about 5 m/s each with their stationkeeping rockets. However, some satellites will malfunction before they can dispose of themselves in this manner, and they must be removed from GEO by other means.

The requirements for retrieving or servicing satellites, removing dead satellites, and removing debris from the geostationary orbit have led to proposals for a geostationary service vehicle such as that by Yasaka and Yasui (1). This service vehicle would use rocket power to transfer to GEO, rendezvous with the targets, and carry out its mission. Hornik and Seboldt (2) propose the use of tethers on such a vehicle to service the European Free Flyer from the international space station Freedom. The use of a tether-equipped service vehicle would allow repeated servicing of the free-flyer to return experiment capsules, using less fuel than required by rockets.

Yasaka(3) has proposed that this service vehicle be used to dispose of inoperative geostationary satellites by the "tumble-orbit transfer" technique. Equipped with a grappling fixture, a 1500 kg service vehicle could reach about 16 geostationary satellites in one year. The service vehicle would attach a rigid arm to the target satellite(Fig. 1), then fire its thrusters to simultaneously increase its orbital velocity and to rotate both vehicles about their center of mass. When the rotating dumbbell pair reached apogee 300 km above GEO, the arm would release the spent satellite into circular orbit, putting the service vehicle into an orbit intersecting GEO(Fig. 2). The service vehicle would then use rocket power to return to GEO. The fuel required by these maneuvers is only two thirds of that required for a docked orbital transfer, assuming the service vehicle and the satellite have the same mass.

Several proposals have also been advanced for the use of tethers for spacecraft orbit changes. Arnold and Colombo (4) first proposed the use of tethers for launching payloads into higher circular orbit from the space shuttle in an elliptical transfer orbit. They developed the equations for tether transfer using both uniform-diameter and tapered tethers. Martinez-Sanchez (5) discusses seven proposal for tether transportation, from shuttle payload launches to space station re-boosting, and derives some general limits on tether mass and taper versus payload mass and delta-v. Both Martinez-Sanchez and Landis and Hrach (6) discuss orbital pumping by tethers to change the orbital energy of a satellite. Landis and Hrach also propose the use of tethers to relocate satellite along the GEO, by extending a long tether, hundreds of kilometers long, to change the orbital period slightly. The satellite would then drift along GEO to a new longitude, retract the tether, and remain fixed in the new desired longitude.

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A very thin tether in GEO can hold a large spacecraft, because the gravity gradient is only 1.6 micro-g per km. A 1500 kg spacecraft on the end of a 300-km tether would therefore produce a force of only 7 N. A tether of Spectra 1000 (7) just 0.5 mm in diameter could hold this load with a safety factor of more than 10. The limitations on tethers result from the deterioration caused by solar ultraviolet radiation and micrometeoroids, and from the wear on the tether caused by winding and unwinding. Tether wear can be minimized by using a protective sheath, such as Nomex, which also protects the tether from atomic oxygen. Collisions with micrometeoroids are a problem that cannot be avoided. The tether would lose one-half of its strength from a collision with a particle whose diameter is at least 30% of the tether diameter (8) For a 0.5-mm diameter Spectra tether of 600-km length, the probability of being hit by a micrometeoroid of 0.15 mm diameter is 2% for a 5-year mission (9). This is a conservative value, because it assumes that the tether will be extended and at risk for the entire mission. In actual application, the total time during which the service vehicle has the tether extended will be less than one tenth of the total life span.

This paper applies these tether concepts to the problem of disposing of geostationary satellites and debris. Two specific tether-assisted methods are studied--the use of long, vertically hanging tethers, and the use of a tether swinging in a pendulum mode.

2. Disposal Using a Hanging Tether

Carroll (7) describes the design of a practical tether service spacecraft for the space shuttle or space station, which could be used to launch spacecraft into higher orbits by a swinging release. The study resulted in the design of a simple tether and deployer system with a total mass of only 10 kg. Carroll notes that the mass of a tether launching system is less than the corresponding rocket system for delta-v of less than 200 m/s. Fig. 3 shows the mass ratios required for rockets (specific impulse of 250 s) and for tethers. Because the tether system mass increases with the square of the delta-v, whereas the mass of a rocket increases linearly with delta-v, rockets are more efficient for higher delta-v requirements. However, the disposal of satellites or debris from GEO requires velocity changes of only about 5 m/s, which puts it in the range in which tethers have the advantage over rockets.

A scaled-up version of this tether and deployer (7) are used as the example tether vehicle in this paper. The vehicle is shown schematically in Figure 4, with a tether storage drum, the tether-end grappling attachment, and a radio-operated remote TV camera to observe the target satellite. The simplest tether disposal technique would be to equip the service vehicle with a tether 600 km long, designed to support the weight of the vehicle and attached satellite at their greatest separation about the geostationary orbit radius. The service vehicle maneuvers into GEO to rendezvous with the target satellite. The end of the tether is attached to the target, and the tether is deployed with the satellite above and the service vehicle below. Because the center of gravity of the configuration remains essentially in GEO, the satellite rises to 300 km above GEO while the service vehicle moves to 300 km below GEO, assuming the masses are identical. Because of tether dynamics, the deployment and retraction each take about a day, with a maximum deployment rate not exceeding 10 m/s. After the tether is fully extended, the satellite is released from the end. Because the satellite at the tether tip is moving faster than circular velocity, it enters an elliptical orbit with a perigee 300 km higher than GEO, and an apogee 2170 km above GEO. Unfortunately, if the service vehicle and the satellite are of equal mass, the service vehicle ends up in an orbit which ranges nearly 14,000 km below GEO, from which it would take a delta-v of 223 m/s to return to GEO.

An alternative technique can be used, however, as shown in Fig. 5. The vehicle can use rocket power to move along the geostationary orbit to rendezvous with a target satellite and dock to it. The vehicle again uses rocket power to move to a second target, still attached to the first. After rendezvous and docking with the second target, the service vehicle extends the two satellites upward and downward unwinding 300-km tethers. It releases the upper satellite first, causing the service vehicle and second satellite to move along the geostationary orbit at 3.3 degrees per day until they reach the next target. Dropping the second satellite then allows the service vehicle to return to GEO with a small delta-v of 1.5 m/s. This method requires that satellites be alternately dropped into orbits 300 km above and 300 km below GEO, rather than all above GEO.

3. Disposal Using a Swinging Tether

Releasing a satellite from the end of vertical tether 300 km above GEO puts the satellite into an orbit with an apogee far above GEO. Some of this excess energy can be transferred to the service vehicle by the use of a swinging tether. The concept is shown in Figure 6. The service vehicle attaches the end of the tether to the target satellite and deploys the tether horizontally. During the deployment, the velocity of the tether is modulated by the tether deployer to excite the tether into a pendulum motion in the plane of the orbit. This tether "pumping" technique is described by Carroll (7). The result is that the spacecraft and service vehicle swing fore and aft on the tether, alternately gaining and losing orbital momentum as the tether moves in its pendulum motion with a period of $1/\sqrt{3}$ of the orbital period.

If the satellite is released on the backswing, it will lose energy and the service vehicle will gain the excess energy. The maximum benefit is obtained if the velocity of the service vehicle is increased enough for it to enter an elliptical orbit that just reaches geostationary altitude. The velocity required at the end of the tether is only 4.8 m/s, which can be achieved with a half-amplitude of only 15 degrees. The service vehicle then retracts the tether, entering an orbit that ranges from GEO to 260 km below GEO. The service vehicle can then drift along, slightly below geostationary orbit, at 1.7 degrees per day until it reaches its next target. A delta-v of just 4.8 m/s will then bring it back into GEO for further rendezvous and disposal.

Table 1. Comparison of Disposal Methods

Operational Phase	Rocket	Tumble Orbit Transfer	Tether Disposal	
			Hanging	Swinging
Transfer to GEO+300	10 m/s	10 m/s	0 m/s	0 m/s
Enter GEO+300	10	0	0	0
Return to GEO	5	5	0	0
Re-enter GEO	5	5	0.8 0	
Rendezvous with Target	0	0	5.7	4.8
Total delta-v	30 m/s	20 m/s	6.5 m/s	4.8 m/s
Propellant per Disposal	23 kg	15.3 kg	4.8 kg	3.7 kg
Tether system Mass	0	0	200 kg	200 kg
Drift Rate	1.8 deg/day	1.8 deg/day	1.0 deg/day	1.7 deg/day

Comparisons of all four methods for satellite disposal are shown in Table 1. The first column describes the maneuvers required, including rendezvous, transfer to the disposal orbit, and returning. The lower part of this column shows the total delta-v required for these maneuvers, and the propellant required, assuming a 1500 kg vehicle and a rocket with a specific impulse of 200 seconds, The second and third columns of the table show the requirements for the conventional rocket technique and for the rocket-based tumble-orbit transfer.

The results of the hanging tether technique are shown in column 4. No delta-v is required for orbit transfers, but 6.5 m/s is required to return the 1500 kg service vehicle to GEO and rendezvous with the next target after each disposal. The results of the swinging tether are shown in the last column of the table. The swinging tether requires only a single delta-v to rendezvous with the target. These results show that tether disposal requires less fuel than the conventional rocket or the tumble-orbit transfer. The swinging tether uses the least fuel of all, at the expense of precise tether libration control. Tumble-orbit transfer is superior to conventional rockets for any number of satellite disposal operations: tether disposal is most sufficient for large numbers of disposals.

4. Tether Deployment Sequence

Tether deployment and retrieval methods have been discussed extensively in preparation for the Tethered Satellite System, a joint NASA-Italian program. TSS-1 will be flown of the shuttle in 1991. The basic theory of tether control during deployment and retraction was developed by Rupp in 1975 (10), based on controlling the tension in the tether.

Simple simulations were conducted using this method to show the deployment sequence. The tether is assumed massless for simplicity, and the masses of the service vehicle and the spent satellite are set identical. Initially, the service vehicle captures the target while its tether is retraced. Then, an impulsive force is applied (by a spring, for example) to give a separation velocity in the radial direction which is perpendicular to the orbital velocity vector. Initially, the service vehicle deploys the tether with a velocity equal to the relative separation velocity. After a while, the tension control law is initiated, and the deployment velocity is adjusted to apply a proper tension to stabilize the subsequent deployment.

Figure 7a shows the history of the extension. In this figure, the vertical axis is fixed to the Earth, and the origin of the coordinates is located on the geostationary radius. After 24 hours of impulse application, the 600-km tether is fully deployed and stabilized along the local vertical. However, since the tether is so long, the gravity force on the lower mass is higher than on the upper. The total gravity force is higher than when both masses were in geostationary orbit before the separation. For this reason, the deployed system is no longer geostationary, although the center of mass is in GEO. Mathematical description of this phenomenon is described by Landis and Hrach in Ref.6. The system moves eastward, as seen in Figure 7a, while the tether axis is maintained vertical. Figure 7b show the behavior of both masses after release.

The spiral-like motion means they are in elliptical orbits. The spent satellite comes down as low as 300 km above GEO, but never lower.

On the other hand, if the tension control law is stopped during the deployment, the tether axis stability is not attained after full extension. Figure 8 shows this maneuver. A swinging motion results. In this case, dampers are inserted at both ends of the tether to damp out longitudinal elastic vibration. The result shows that the tension control law cut maneuver can be an alternative to the previously mentioned "pumping" technique. A refinement of the amplitude adjustment can of course be made by the pumping, so that a desirable release velocity can be obtained.

5. Conclusions

Two tether techniques have been investigated for the disposal of spent geostationary satellites or GEO debris. These involve the use of hanging or swinging tethers used by a service spacecraft. The mass of the tether and deployer required for either technique compares favorably with conventional rockets, and even with the tumble-orbit transfer technique of Yasaka, for multiple disposal operations. The time required for each tether-assisted disposal is about 50% longer than the rocket techniques, mainly due to the time required for tether deployment and retraction. The swinging tether technique requires the least propellant, but it requires more sophistication in the tether control.

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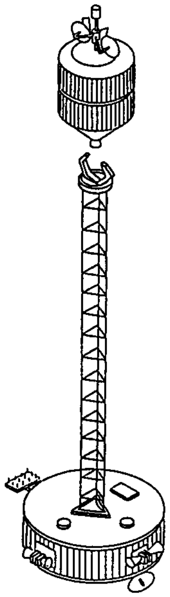


Fig 1 Tumble Orbit Transfer Vehicle with Grapple Arm

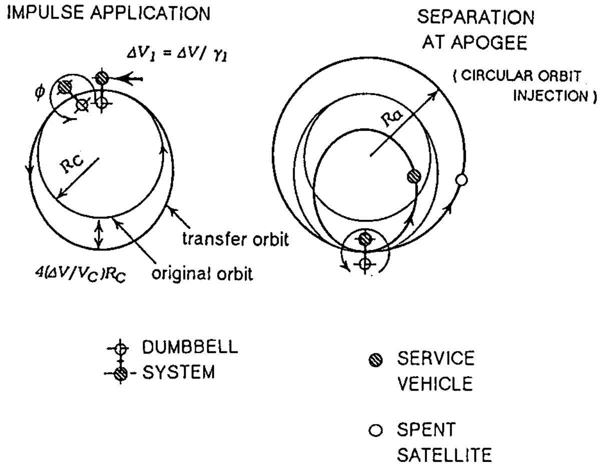


Fig 2 Tumble Orbit Transfer Disposal Technique

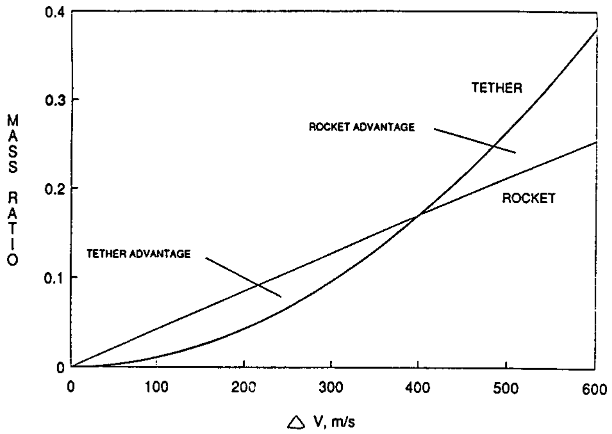


Fig 3 Mass Ratios for Rocket vs Tether Velocity Change

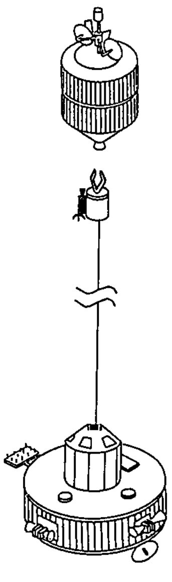
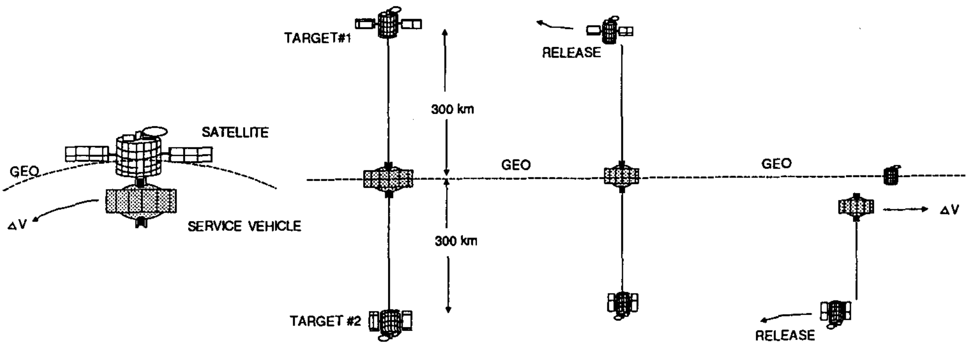


Fig 4 Conceptual Service Vehicle with Tether



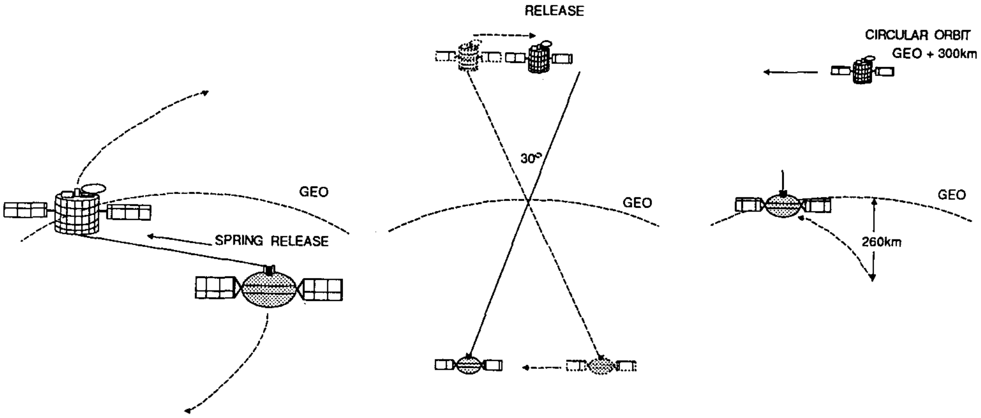
a. Attach to first target and transfer to second target

b. Rendevous with second target and extend tethers

c. Release upper satellite and drift to third target

d. Release lower satellite and transfer to next target

Fig 5 Hanging Tether Disposal Technique

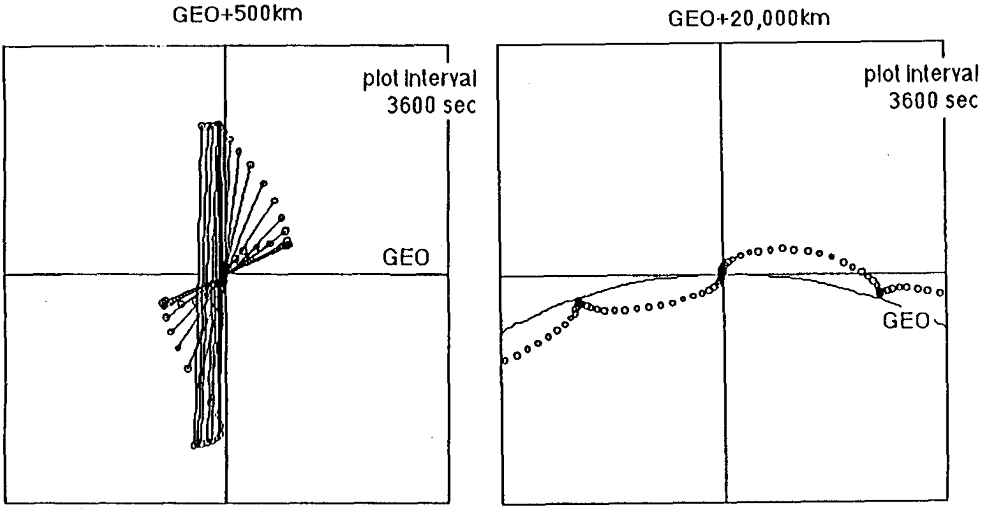


a. Service vehicle attaches to spent satellite and extends tether horizontally

b. Satellite is released on backswing to insert it into circular orbit at GEO+300km

c. Service vehicle retracts tether and returns to GEO by rocket

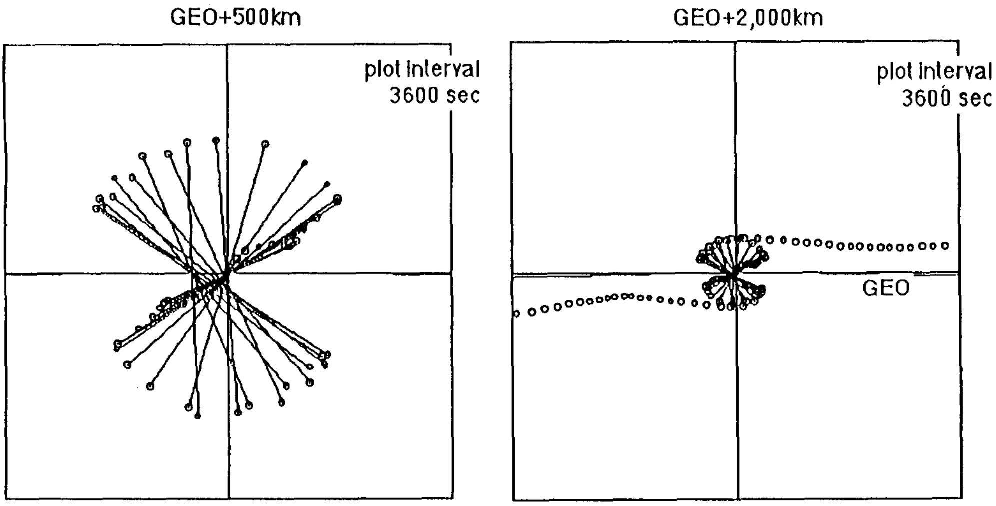
Fig 6 Swinging Tether Disposal Technique



a) Time History of Tether Extension

b) Behavior of Masses After Release in Hanging Tether

Fig 7 Tether Deployment with Tension Control



a) Swing Motion by Tension Control Cut Maneuver

b) Behavior of Masses in Swinging Tether Disposal

Fig 8 Tether Deployment With Tension Control Cut Maneuver