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THE IMPROVED TERESA-CONCEPT FOR THE REMOVAL OF LARGE SPACE DEBRIS OBJECTS

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ABSTRACT

Near earth orbits are overcrowded with useless space objects like inactive payloads, spent upper stages and fragments - Space Debris. If spaceflight is continued as in the past, the critical level for the setting in of a cascade of collisions will be reached within the next decades. A cascading effect is caused by collision fragments actuating new collisions, mainly triggered by larger objects. Therefore the population in orbit, especially of larger Space Debris, should be limited as early as possible. If it is not possible to limit the population by preventive measures, active removal of numerous larger objects from higher altitudes may be the only solution. In this paper the improved TERESA-strategy for active, economical removal of large Space Debris will be presented.

1. INTRODUCTION

Within the scope of more than 35 years of space flight activities there are, apart from numerous positive consequences (e.g. improved telecommunication, information on harvests, weather), also some negative accompaniments: a serious high number of objects in orbit which cannot be used any more - Space Debris.

The term Space Debris includes inactive payloads, spent rocket upper stages, explosion and collision fragments and mission related objects like clamp bands, separation bolts etc.. There are more than 100,000 objects above 1 cm in diameter with increasing tendency (Ref. 1).

If spaceflight is continued as in the past, the critical level for the setting in of a cascade of collisions will be reached within the next decades (Ref. 2).

A cascading effect is caused by collision fragments actuating new collisions. This process is triggered mainly by the larger objects, as simulations have shown. Fig. 1 shows the long term evolution of the population with and without objects < 10 cm in the basic population. The basic population consists of active and inactive payloads and rocket upper stages, mission related objects and explosion fragments. For the scenario without untrackable objects all small objects have been removed. Also the generation of small explosion fragments and mission related objects has been suppressed. Even in this unrealistic case a cascading effect of collisions will set in, only delayed. These simulation results are quite reliable because they are based on deterministic known, trackable objects.

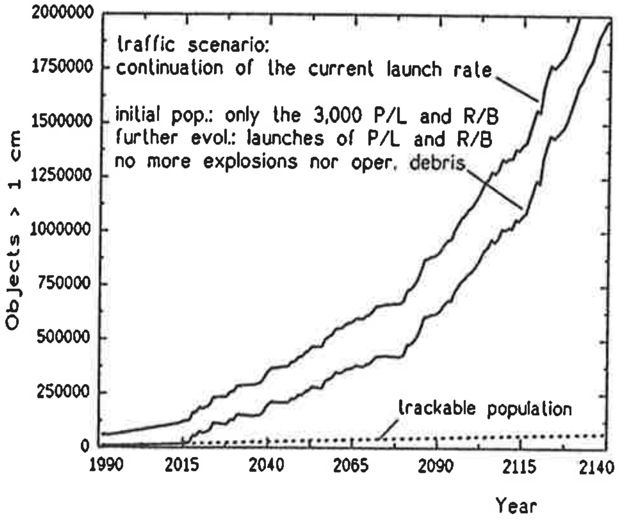

Figure 1. Longterm evolution of the population with and without objects < 10 cm (steady increase of the basic population of 5 % for 50 years)

For both scenarios a realistic increase of the respective basic population of 5 % linear for about 50 years has been assumed.

Summarizing it can be said:

- spaceflight cannot be continued as in the past
- the large objects are of paramount importance for the future development of the population.

The consequence has to be a limitation of the population to an uncritical level in time. In this way the threatening exponential increase of the total population due to random collisions could be avoided. Preventive measures like de-orbit manoeuvres of payloads and upper stages at the end of their mission could be carried out to reduce the population growth.

2. ACTIVE REMOVAL

Supposing it is not possible to limit the population especially of the larger objects by preventive measures, active removal may become necessary, though it is much more difficult and expensive.

Fig. 2 shows the effectiveness of the combination of preventive measures and of subsequent active removal of 3000 large objects from altitudes above 700 km. It can be seen that a cascading effect of collisions can be avoided, if

- large objects are removed (more than about 100 kg per object)
- several hundreds to thousands large objects are removed
- removal takes place in high altitude regions where the lifetime of the objects is high due to the almost missing self-cleaning effect of the earth's atmosphere.

The mean curve illustrates that only de-orbit manoeuvres of rocket upper stages and payloads at the end of their missions, established in 2010, are not sufficient. Active removal is necessary as well: the sooner active removal starts, the lower the population level will be.

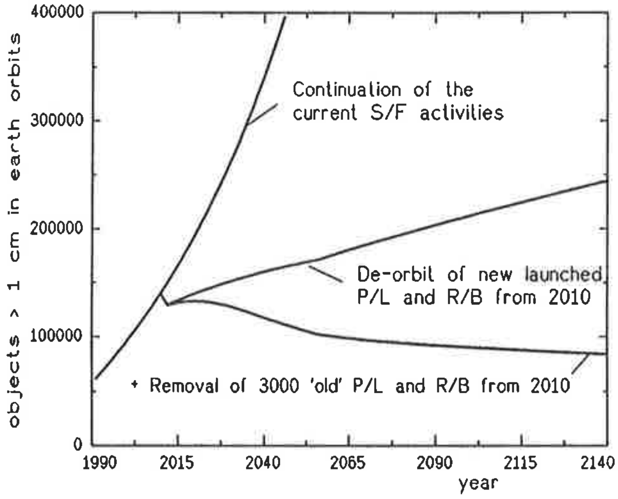

Figure 2. The effectiveness of preventive measures and of subsequent active removal of large objects from high altitudes

3. THE TERESA CONCEPT FOR ECONOMIC SUBSEQUENT ACTIVE REMOVAL OF NUMEROUS LARGE OBJECTS FROM HIGH ALTITUDES

In view of the foregoing requirements concerning active removal the strategy called TERESA has been developed (*TE*thered *RE*mover *SA*tellite): a cycle consisting of transfers of orbital energy with the help of a space tether. Each object is de-orbited separately by decreasing its orbital energy. A decisive advantage of this concept compared to conventional methods is the drastically reduced propellant consumption per necessary Rendezvous und de-orbit manoeuvre. Thus numerous large objects can be removed by operations within one single mission.

The strategy basically consists of the following 4 phases (see also Fig. 3):

Phase 1 The remover satellite TERESA performs Rendezvous and Docking with the target object, which is selected from objects in a very narrow inclination and a suited altitude region, which is possible as detailed investigations have confirmed (see also Ref. 4)

Phase 2 transfer of orbital energy from the debris object to the remover with the help of a tether → roping down of the debris object towards earth; in this way the orbital energy of the debris object is reduced without propellant

Phase 3 adjustment of an elliptical, *optimized* transfer orbit with the help of electrodynamically generated thrust, i.e. conversion of orbital energy into electrical energy → electrodynamic deceleration thrust; the transfer orbit is optimized with respect to different parameters like the mass of TERESA and the debris object, the initial altitude etc.

Phase 4 separation of the debris object from the tether at the right moment and at the right place; criteria: 1. Re-entry of the debris object; 2. TERESA's orbit after the separation has to be very similar to the orbit of the next target object to save Δv for the next Rendezvous manoeuvre (*phase 1*)

For the generation of electrodynamic thrust a conductive tether is necessary. If the electrodynamic thrust can be used, the propellant demand for orbit accomodations can be saved to a large extent. As 'electrodynamic effect' commonly the following physical phenomenon ist denoted: a tethered system orbiting the earth with a high velocity crosses the geomagnetic field lines. Choosing a conductive tether a voltage will be induced between the end masses of the tether. If the electrical circuit is closed by plasma contacts via the conductive layers of the earth's atmosphere, a current within the tether is induced. This current interacts with the geomagnetic field and causes a decelerating force on the tether (Lorentz force). In this way orbital energy can be annihilated.

In the case the electrodynamic effect can not be used due to an unsufficient electron density in high inclination and altitude regions, which are interesting

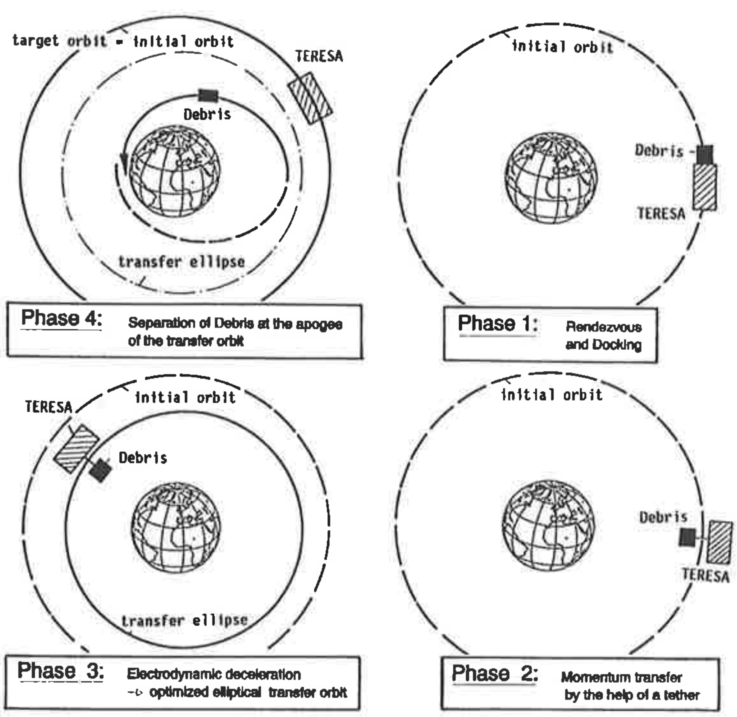

Figure 3. The 4 phases of the TERESA-strategy: a cycle consisting of energy transfers with the help of a tether

for TERESA (Ref. 4), conventional thrust has to be used. This means that the roping down of the debris object will be carried out in phase 3. The elliptical transfer orbit will be adjusted in phase 2.

Using electrodynamic thrust about 85 to 125 objects can be removed within about 7 years. Due to a higher propellant consumption per removed object when conventional thrust is employed, about 50 % less objects can be removed. Conventional thrust has the advantage that there is no dependence on the earth magnetic field strength and the electron density, which can not be influenced actively. In this case a mission will take only about 3 years.

4. THREAT TO THE TETHER POSED BY SPACE DEBRIS

A serious threat to all tether applications and therefore also to TERESA poses Space Debris itself, namely the cutting of the tether by already small particles with a diameter of about 7 % of the tether diameter (Ref. 5). This means that a tether with a typical diameter of about 2 mm can already be cut by particles ≥ 0,14 mm. In 900 km within one year about 260 impacts of particles ≥ 0.1 mm on a tether of 100 km length have to be expected (Ref. 6 and 7).

To reduce the collision risk for the tether the necessary tether length for re-entering debris objects has to be as small as possible.

The use of a swinging tether is a possibility to reduce the necessary tether length without additional Δv, as will be shown in the next chapter. For a further, decisive reduction of the tether length a rotating tether is currently investigated. Swinging or rotating tethers should preferably be used when no electrodynamic thrust is employed.

5. THE USE OF SWINGING TETHERS FOR TERESA

When the debris object is roped down towards the earth, a Coriolis force perpendicular to the tether occurs.

$$\vec{F}_{Co} = 2 m_1 \, (\vec{v}_{rop} \times \vec{\Omega}_{Sys}) \qquad (1)$$

where m_1 is the debris mass, v_{rop} is the roping down velocity and Ω_{Sys} is the angular velocity of the tether system. The result of this Coriolis force F_{Co} is a deflection of the tether in flight direction (see Fig. 4).

For a certain roping down velocity the deflection angle can be kept constant. This is possible, when the Coriolis force compensates the centrifugal and gravity forces while roping down. Therefore the roping down has to be carried out with an exponentially increasing velocity v_{rop} (see eq. 2 (Ref. 8)).

$$v_{rop} = \frac{3}{2}\,\Omega_{Sys}\,l_0\,e^{\frac{3}{2}\Omega_{Sys}\,t\,\cos\alpha\,\sin\alpha}\,\cos\alpha\,\sin\alpha \tag{2}$$

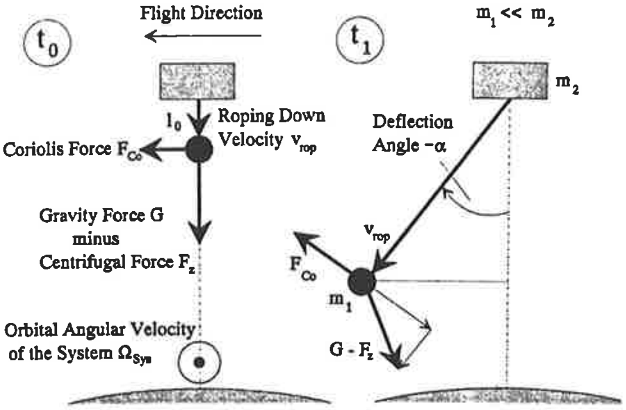

Figure 4. The Coriolis force acting on the tether system while roping down

At the end of roping down the tether starts swinging. This means that the swinging of the tether can be achieved without any propellant.

5.1 Interrelations between different system parameters

Employing a swinging tether the two requirements concerning *phase 4* have to be fulfilled as well:

- Re-entry of the debris object after the separation
- TERESA' s orbit after the separation has to be as similar as possible to the orbit of the next target object, i.e. the orbit has to be almost circular

After roping down the debris object, TERESA is too fast for its new, increased altitude, compared to a free flying object. By electrodynamic breaking forces the orbit of the whole configuration is lowered and made elliptical. The debris object is separated from the tether at the apogee. So TERESA's velocity at the moment of separation is almost equal to the velocity of a free flying object at the initial circular orbit. For simplification, the initial orbit is assumed to be the orbit of the next target object.

Fig. 5 shows the interrelation between the deflection angle of the tether after roping down with a constant angle of -45°, the true anomaly and the resulting perigee of the debris object after the separation. It can be seen that the debris object re-enters when the separation is carried out in the local vertical ($\alpha = 0°$) during the backward swing (change of the sign of α from "-" to "+"). This state of the system has to be reached at the apogee of the elliptical orbit. There the difference between the velocity of the lower mass and the velocity of a free flying object on a circular orbit with the respective altitude is maximal.

The additional deceleration impulse resulting from the swinging is maximal during the backward swing in the local vertical. The slower the debris mass is, the lower will be its perigee after the separation. At the upper mass it is the other way round: when the deceleration of the debris object is maximal, TERESA's acceleration is maximal.

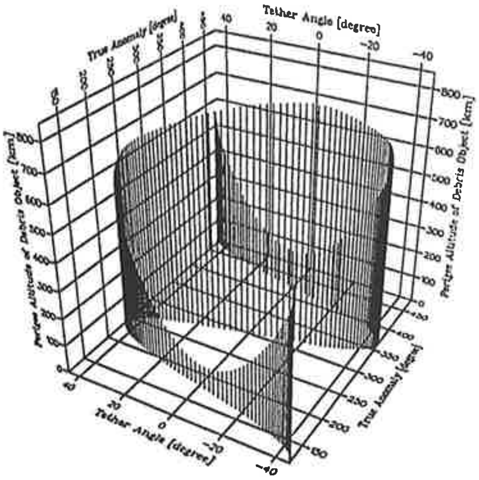

Figure 5. Perigee altitude of the lower end mass after the separation from the tether as a function of the true anomaly of the separation point and the tether angle ($m_{Debris} = 2$ t, $m_{TERESA} = 11$ t, transfer orbit eccentricity: 0.0106, tether length: 93 km, altitude TERESA should achieve: 1100 km)

The necessary tether length for different tether angles is shown in Fig. 6.

The larger the initial tether angle is, the larger is the velocity contribution from the backward swing in the local vertical. Subsequently the necessary tether length decreases.

The necessary tether length for re-entering a debris object is about 146 km, assuming almost no tether deflection ($\alpha = 5°$, initial altitude: 1100 km). When the tether angle is about 45°, the tether length can be reduced to about 93 km. A tether angle of 85° causes stability problems when the tether should swing for a while. Such a large angle can be used without problems only for one backward swing. If this ispracticable a tether length of only about 80 km is sufficient.

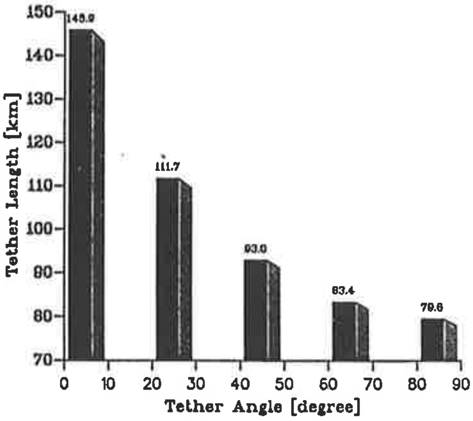

Figure 6. Necessary tether length for re-entering a debris object as a function of the tether angle α (altitude of TERESA after the separation: 1100 km, vertical separation at the apogee during backward swing)

Regarding an optimized transfer orbit, the necessary tether length is independent of the debris mass (m_{TERESA} = 11 t = const.). The debris mass influences the transfer orbit eccentricity and its apogee altitude (see Fig. 7 and 8).

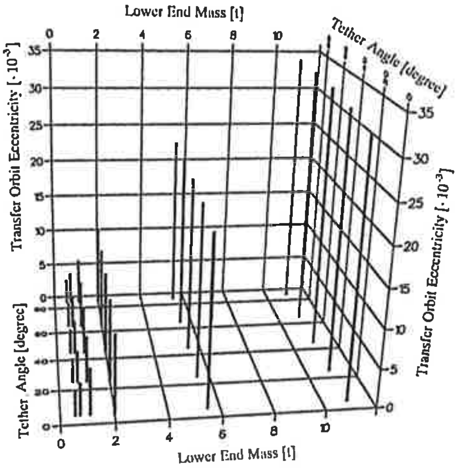

Figure 7. Necessary transfer orbit eccentricity for re-entering a debris object as a function of the debris mass and the tether deflection angle (altitude of TERESA after separation: 1100 km, m_{TERESA} = 11 t, vertical separation at the apogee during backward swing)

The larger the debris mass is, the more elliptical the transfer orbit has to be and the lower its apogee has to be located. The necessary transfer orbit eccentricity is no function of the tether angle. The tether angle only influences the necessary tether length.

When both end masses are equal, the altitude increase of the upper mass while roping down is almost equal to the altitude decrease of the lower mass. To fulfill the requirement that TERESA's orbit after the separation should be unchanged compared to the initial orbit (altitude: 1100 km), the transfer orbit apogee has to be reduced by electrodynamic breaking forces correspondingly.

The distance of the upper mass from the orbit of the center of motion of the tether system at the end of roping down is maximal in the case of equal end masses. TERESA's orbit after the separation is almost circular and similar to the initial orbit, when before the whole configuration is lowered down sufficiently. Additionally this lowered (transfer) orbit of the configuration has to be quite eccentric.

The lowered ellipitical transfer orbit guarantees that the debris object reenters, when is is separated from the tether at the apogee during the backward swing and in the local vertical.

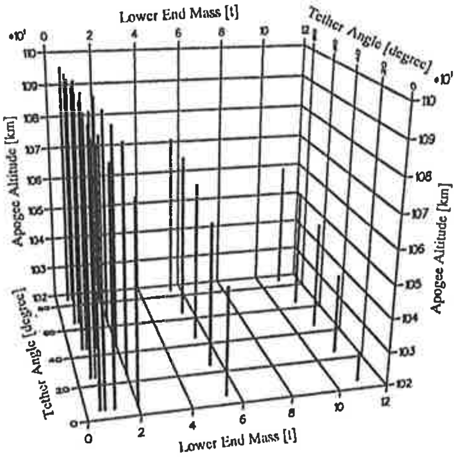

Figure 8. Apogee altitude of the transfer orbit for re-entering a debris object as a function of the debris mass and the tether deflection angle (altitude of TERESA after separation: 1100 km, m_{TERESA} = 11 t, vertical separation at the apogee during backward swing)

When the lower end mass is very small (e.g. 550 kg), the transfer orbit is quite similar to the initial orbit, i.e. the final orbit of TERESA ($h_{A\ transfer}$ = 1096 km, $h_{P\ transfer}$ = 1047 km, initial orbit: 1100 km).

Principally the necessary tether length and the transfer orbit eccentricity increase with the altitude. This corresponds with the increasing Δv demand for a re-entry manoeuvre.

5.2 Δv savings

In order to make a debris object re-enter, its perigee altitude has to be about 80 km. Assuming an initial circular orbit in 1100 km altitude, a deceleration impulse of about 272 m/s is necessary. This means for an object of 2 t about 254 kg of propellant (mean exhaust velocity of liquid propellant: 2000 m/s).

When momentum transfer with the help of a tether and an elliptical transfer orbit are employed, the necessary Δv to reach the transfer orbit is only about 48 m/s. This Δv demand can be saved by the utilization of electrodynamic breaking forces, when the tether is conductive. The necessary tether length is about 146 km.

When a swinging tether with a maximum deflection of 45° is used, the Δv demand to adjust the transfer orbit is almost unchanged (45 m/s). With the help of a swinging tether only the necessary tether length and therefore the collision risk can be reduced. The necessary length is only about 93 km.

When the requirements for both end masses have to be fulfilled (see chapter 5.1), it is not possible to use a longer, swinging tether and a different transfer orbit to save Δv.

6. SUMMARY

The prevention of the setting in of a cascading effect of collisions requires active removal. An efficient and economic method to remove numerous large objects from high altitudes is the TERESA strategy (TEethered REmover SAtellite): a cylcle consisting of transfers of orbital energy with the help of a space tether.

A serious threat to all tether applications and therefore also to TERESA poses Space Debris itself, namely the cutting of the tether by small particles with a diameter of about 7 % of the tether diameter. Such particles have already high abundance.

To reduce the collision risk, the employment of a swinging tether has been investigated. It has been shown that the tether length can be reduced in this way by about 45 % at maximum (tether angle 85°) without additional Δv.

The necessary tether length depends on the initial altitude and on the tether deflection angle. The smaller the angle is and the higher the initial orbit is, the longer the tether has to be.

The eccentricity and the apogee altitude of the transfer orbit depend on the debris mass: the heavier the debris object is, the more eccentric and the lower the transfer orbit has to be.

For a further reduction of the necessary tether length a rotating tether is currently investigated.

The TERESA concept and its further investigations and improvements are an attempt to answer one of the many questions concerning the Space Debris problem. Work still has to be done to develop a suited remover vehicle and realistic, optimized missions.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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