Tethers and Asteroids for Artificial Gravity Assist in the Solar System

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Planetary missions have benefited greatly from the gravity assist mechanism where a planetary flyby can boost or otherwise modify a spacecraft trajectory to accomplish specific goals. The multiplanet encounters of Voyager 2, for example, were accomplished using this process. The Galileo mission will utilize over a dozen flybys of the Galilean moons to perform a complete scientific investigation of the Jupiter system. Can asteroids be used in a manner similar to gravity assist? Their gravitational pull is too weak to provide the required bending of the trajectory, but this turning can be done by means of a tether. For example, the spacecraft may release a 100-km tether that will attach itself to an asteroid it approaches. The spacecraft then will be forced to turn in a long arc, which can be terminated upon release of the tether when the proper vector is obtained. The primary limitation of using this process will be tether strength which, with today's technology, will not allow relative velocities to exceed 1-3 km/s. This and other limits are investigated, as well as some mission possibilities using this method. Methods of tether/asteroid attachment and release will be discussed as well.

Introduction

"GRAVITY assist" is the term given to the effective use of the gravitational field of a massive body to deliberately modify the trajectory of a flyby spacecraft. For example, the two Voyagers[1] utilized the gravity assist of Jupiter to give them additional energy to continue their flight to Saturn. Jupiter not only provided a needed velocity boost so that it could reach the orbit of Saturn, but also turned the trajectories through just the angles needed so that the spacecraft would intercept the planet. Voyager 1 is headed out of the solar system, but Voyager 2, with a gravity assist by Saturn, will encounter Uranus in 1986, and then, again via gravity assist, will encounter Neptune in 1989. Similar gravity assist missions were Mariner 10, which flew by Venus before going to Mercury,[2] and Pioneer 11, which used a Jupiter gravity assist to lob it out of the ecliptic plane and across the solar system to Saturn.[3]

It is the ability of a massive body to bend a spacecraft trajectory in a near-collision approach that is essential to the gravity assist process. Jupiter is very massive, and will bend the spacecraft trajectory through a large angle of the order of 180 deg. In contrast, the asteroids have such low surface gravity that flybys of them are nearly rectilinear. If, however, in the course of a flyby, a spacecraft can be attached to an asteroid with a tether, then the spacecraft can swing around the asteroid through a large angle to accomplish the same type of trajectory change as gravity assist from a massive planet. Here, more about benefits than about means will be discussed, hoping to stimulate the process leading to the utilization of asteroids in a mode similar to gravity assist.

Dynamics and Limitations of Gravity Assist

A gravity assist is kinematically equivalent to an elastic collision of two bodies, which produces a momentum exchange between them. It is an example of a "soft" collision, as compared to a hard collision involving actual surface impact. In the case of Voyager 2, in a gravitational encounter with Jupiter, an observer on Jupiter will see the spacecraft travel a hyperbolic path, and the spacecraft's outgoing speed will equal its incoming speed. However, a momentum increase (or decrease) will be seen by a heliocentric observer. Thus in a direct flyby of Jupiter, Voyager 2 experienced a velocity increase of several kilometers per second, permitting it to fly out to Saturn. On the other hand, a retrograde flyby of Jupiter will be needed for the Starprobe spacecraft to lower its sun relative velocity and cause it to fall to within 4 solar radii of the sun.[4]

Although gravity assist by the planets and the large planetary moons (such as the moons of Jupiter for the Galileo mission)[5] is a useful technique for expanding our capability to explore the solar system, the assisting planet or moon must be at the right place at the right time. Therefore, launch opportunities are restricted; favorable dates may be years apart. In an extreme case, the Voyager 2-type mission to the four giant planets will not be available again for 175 years.[6]

Knowing the mechanism, value, and limitations of planetary gravity assist, is there an alternate means of producing the same effect with the smaller but more numerous asteroids or comets? At the current level of space operations the answer is no, but with the development of tethers, which is now in the infant stage, it may be possible in the future. Since tethers are so new in space applications, some examples that are being seriously considered will be given. The realization that some applications have already been assigned Shuttle flight target dates may remove a somewhat science fiction aura that has surrounded the tether concepts.

Considering that there are thousands of asteroids greater than 1 km in diameter, the opportunities for utilizing gravity assist through soft collisions will expand by orders of magnitude. More asteroids will be discovered and smaller ones will be even more numerous. Those as small as 10 m in diameter will weigh over 1000 metric tons and could also be effectively used.

Some Proposed Tether Applications

In 1988, it is planned to conduct some Shuttle-based tether experiments from orbit at a 200-km altitude in space.[7] In the first experiment, a 200-kg satellite made by an Italian team will be deployed 30 km above the Orbiter, connected to the Shuttle by an electrodynamic tether. Measurements will be made of the electric power generated as the tether moves through the geomagnetic field, and reciprocally of the thrust developed as a current is passed through the tether.

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On a second Shuttle launch, the same Italian spacecraft with different instruments will be suspended on a tether 100 km below the Orbiter to measure the atmospheric properties in a region where the Orbiter itself cannot fly. This experiment will analyze the aerodynamic and aerothermal interactions in a density regime where there will be some departure from free molecule flow. This tether has a circular cross section 2 mm in diameter with an inner core of Kevlar 49 and an overcoating of Teflon to protect the Kevlar from interaction with atomic oxygen and from solar uv exposure. In both flights, the tether dynamics will be studied and controlled as the tether and satellite are deployed into their gravity-gradient-stabilized position, and again as the satellite is reeled back into the Orbiter cargo bay.

In another proposed application,[8] tethers are used to assist in the transfer of payloads from low-Earth orbit (LEO) to geosychronous orbit (GEO). A Shuttle payload in LEO is deployed upward on a long tether. By taking advantage of the deployment dynamics, one can arrange that at the minimum altitude, the payload, swinging in an arc about the Shuttle payload center of mass, is moving so that the swinging velocity is in the direction of the orbital motion. At that point the payload is released. It moves in a new orbit with a higher perigee than the Shuttle, and a much higher apogee due to the velocity from both the swinging motion and the Shuttle angular velocity. At apogee it is caught by a tether lowered from a station in circular orbit. Since the payload usually will have a lowered velocity than the station, it will revolve in a circle about the station while constrained by the tether. The two masses can remain in this rotating configuration until the payload is released at its highest point to attain a yet higher orbit. Another station at a still higher altitude can repeat the catch-and-release process so that the payload eventually reaches GEO. We have computed that two or three stations would be needed if the tethers are to be made of an existing material such as Kevlar.

Upon closer examination, it can be seen that this method of momentum transfer, where the station loses the momentum that the payload gains, is a soft collision similar to a gravity assist. In this case, the station takes the place of the planet.

Tether Strength Requirements

Assuming, at present, that some means have been developed for attaching a tether to an asteroid during a flyby, it is possible to determine the tether strength requirements as a simple function of the relative velocity (V_i) and the payload-to-tether-mass ratio. In these calculations, the asteroid is considered as an anchor point only, and its gravity gradient effect on the tension in the tether is neglected.

The spacecraft, of mass M and velocity of approach V_i, is swung in a circular arc of length L about the asteroid. At the spacecraft end, the tension is $T_L = M\omega^2 L$, where $\omega = V_i/L$ is the angular velocity of revolution. This represents a boundary condition on the system. If the tether has a constant cross-sectional area A and mass density ρ, the differential equation for the tension T as a function of radius r is

$$\frac{\mathrm{d}T}{\mathrm{d}r} = -A\rho\omega^2 r \tag{1}$$

and the stress in the tether is $S = T/A$. The solution to this equation with the boundary condition above is

$$SA = T = M\omega^2 L + \frac{\rho A \omega^2}{2}(L^2 - r^2) \tag{2}$$

We will choose the cross-sectional area A to make the stress at the origin (where the stress is greatest) to be the safe working stress S_0 of the tether material. We can then obtain the tether mass $m = \rho A L$. After some algebraic manipulation, we can find the spacecraft-to-tether mass ratio as

$$\frac{M}{m} = \left(\frac{V_c}{V_i}\right)^2 - \frac{1}{2} \tag{3a}$$

$$= \delta\left(\frac{C_L}{V_i}\right)^2 - \frac{1}{2} \tag{3b}$$

where the characteristic velocity is calculated as $V_c = \sqrt{S_0/\rho}$. In the second equality, the stress S_0 has been replaced by $S_0 = \delta E$, where E is Young's modulus and δ is the safe working strain, and the fact that the longitudinal sound velocity is $C_L = \sqrt{E/\rho}$ has been used.

This equation shows that as the spacecraft mass approaches zero, there is an upper limit to the velocity that can be constrained by the tether, namely, $V_{i\max} = \sqrt{2\delta}C_L$. This result is remarkable in that this limit does not depend upon the spacecraft mass or tether length. It is an intrinsic property of the tether material. For Kevlar 49, $C_L = 10$ km/s, and a good value for the working strain is $\delta = 0.01$. (Actually, the breaking strain is $\delta_B = 0.02$, therefore, we have an adequate, but not generous, safety factor of 2 in the working strain.) Then, the characteristic velocity is $V_c = \sqrt{\delta}C_L = 1$ km/s, and the maximum spacecraft velocity is $V_{i\max} = 1.4$ km/s.

Equation (3b) places limitations on the achievable relative velocities for a given material and a given spacecraft-to-tether mass ratio M/m. A plot of this relation for Kevlar and stronger materials is given in Fig. 1.

This velocity limitation may be circumvented in two ways. First, from Eq. (1), since the tension decreases as the distance from the center of rotation increases, it is possible to decrease the cross-sectional area accordingly. The solution is an exponentially tapered tether (see Ref. 9, for example). Unfortunately, the tether mass required increases rapidly with velocities larger than V_c. For example, for $V_0 = 2V_c$, the tether-to-spacecraft mass ratio is 17.7. Thus, flyby velocities should be restricted to the characteristic velocity or less, except for situations where the tether is reused extensively.

A higher velocity may be achieved, however, through control of tether tension by paying out or reeling in the tether. It has been assumed that the spacecraft-asteroid tether attachment will occur when the velocity vector is exactly perpendicular to the radius vector between the two. Normally, however, there will be a radial component of velocity that the tether system must handle. If this component is outward, then the tether must be payed out to avoid the tether tension exceeding some maximum. If the component is inward, then the tether should be reeled in to ensure rotation of the spacecraft. Higher velocity than the limit may be handled by paying out the tether when the maximum tension would otherwise be exceeded. This cannot go on indefinitely, therefore, at some point the tether must be detached. Higher velocities, then, will limit the turning angle available for artificial gravity assist.

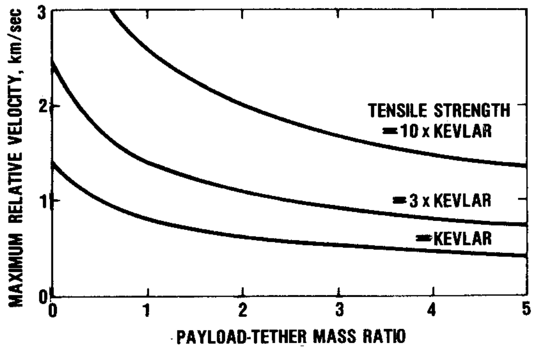

Fig. 1 Velocity limitations for various payload-tether mass ratios and tether strength.

Methods of Tether Attachment to Asteroids

The material strength of the asteroid surfaces will not be known in detail when a tether assist mission is designed, therefore, the methods by which tethers are attached should be largely independent of surface characteristics. For small bodies, say 10 min in diameter, the entire asteroid could be surrounded by a fishnet-type structure made of flat Kevlar tape which when drawn tight does not place a concentrated load on any surface portion. As a single numerical example for orientation purposes, consider a Kevlar net engaging the 10-m-diam asteroid with tapes 0.01-g/cm^2 thick that cover 3% of the asteroid surface. This net will have a mass of 1 kg only, yet will be able to sustain a force of 10^5 N applied to its drawstring. A spacecraft of 1000 kg traveling at 1 km/s past the asteroid, and held by a 100-km tether will generate a centrifugal force of only 10^4 N, which could be held safely by the net.

For large bodies with strong surface structures, the tether end could be fastened to a ground penetrator that would anchor into the asteroid. The penetrator would be left behind when the tether is released to let the spacecraft fly off.

For large bodies of about 1 km in diameter with a highly brecciated surface that would have little mechanical strength, there may be nothing worthwhile for the tether to hold onto, and the fishnet required to englobe the asteroid would be too massive. It is suggested that the tether end have a plow-shaped device which the spaceraft drags along the asteroid surface. The plow exerts a force on the tether, due not to the strength of the surface it breaks up, but to the inertia of the material it displaces. Preliminary calculations show that appropriate tensions can be sustained with plow masses substantially smaller than the spacecraft mass. However, some active control system is necessary to cushion the shock if the plow hits a strong surface feature.

Mission Capabilities for Artificial Gravity Assist

The velocity limitations just derived place some restrictions on the general use of artificial gravity assist. For example, none of the Jupiter flyby missions mentioned earlier could have been accomplished by this alternate method, since the relative velocity (V infinity) exceeded 6 km/s in all cases. Because of this velocity limitation, each application must be examined carefully. For example, in an asteroid belt tour it is quite likely that a series of hops could be made with less than 1 km/s velocity difference in each. Furthermore, the tether method might well be aided by some rocket propulsion to reduce the velocity difference, since in any event propulsion would be necessary to achieve a close enough approach to use a tether.

Given the velocity limitations for soft collisions imposed by tether strength, it is possible to compute the orbit change available using this technique. Assuming a circular orbit for the asteroid (eccentric orbits with the same major axis give similar results), a soft collision with it, using a tether, will allow departure in any direction from the asteroid. The most favorable departure direction, to enlarge the orbit, is in the direction of the asteroid's orbital motion about the sun. The aphelion increase in terms of the radius of the initial orbit and the relative velocity is given in Fig. 2.

For an asteroid in the Earth's orbit, for example, having an orbit radius of 1 a.u., about 3 km/s are required to reach out to Mars orbit which is at about 1.5 a.u. A velocity of 1 km/s will only extend about 0.15 a.u. from the Earth's circular orbit.

Applying Fig. 2 to larger orbits, this technique is more effective. A tethered swing around an asteroid in Mars' orbit will extend the spacecraft aphelion out to 2.5 a.u., assuming a relative velocity of 3 km/s. This is still not as effective as a gravitational assist by Mars itself. At one phase in the Galileo mission design, for example, a close flyby of Mars was proposed to boost the spacecraft out to Jupiter, which is at 5.2 a.u.[10]

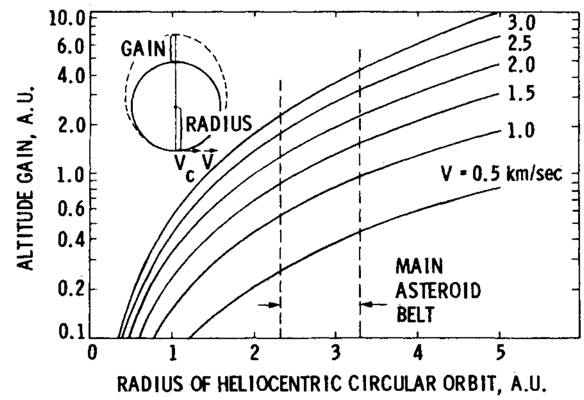

Fig. 2 Aphelion altitude gain for velocity applied to circular orbits.

The effectiveness of tether-asteroid assist improves considerably at the main asteroid belt and beyond. At Jupiter's orbit, for example, a tethered spin around with a relative velocity of 2 km/s will extend a spacecraft orbit to 10 a.u., or out to Saturn. Near Jupiter thre are many small bodies, which are possibly available for a tethered artificial gravity assist. Attending the planet itself, in addition to the four large Galilean moons, there are eight other smaller satellites orbiting at large distances. Their sizes are estimated to range from 1 to 50 km in diameter. Furthermore, as a result of Jupiter's influence, over a dozen known asteroids cluster about the two Trojan points located in Jupiter's orbit 60 deg ahead and behind Jupiter itself. Very likely there are many much smaller undiscovered trojans oscillating about these two stable points. In the future, when missions are flown to these asteroid groups, perhaps the soft collision techniques presented here may be of some benefit.

Mission Applications

No specific missions using this technique have been calculated in detail, but some mission applications will be described to illustrate its potential. Some applications show how this tether assist method may ease the propulsion requirements of previously considered missions, and some show how the method may open up new mission possibilities.

Mars Missions

A Hohmann transfer from Earth orbit to Mars orbit requires velocities of about 3-4 km/s. Using an intermediate tether-asteroid assist between Earth and Mars can reduce the propulsion requirements by about 50 %. The relative velocity requirements at the asteroid would be about 1.3 km/s, requiring a spacecraft-to-tether mass ratio of 0.1 for Kevlar (Fig. 1) or 1.2 for a tether three times stronger. An Aten-type asteroid, which has an aphelion less than that of Mars, and whose orbit is nearly in the ecliptic, would be a suitable intermediary. It is estimated that about 2500 asteroids with diameters greater than 1 km are in suitable near-Earth orbits. Probably, there are enough of these bodies so that the Earth-asteroid-Mars phasing problem would disappear, since at any launch time one of them would be in a proper position to accommodate a tethered assist.

Outer Planet Missions

Transfer velocities from Earth to Jupiter orbits and beyond are much greater: 9 km/s compared with 3 km/s to reach Mars. A Mars true gravity assist to Jupiter can reduce this transfer requirement to about 6 km/s. Instead of Mars, a suitable asteroid in the main belt could be used with the tether artificial gravity assist method. Phasing would not be a problem, as it would be for Mars itself, since many of these asteroids are fairly evenly distributed in near-circular orbits, and are close to the ecliptic.

An even more advantageous method would be to transfer to Mars' orbit with about 4 km/s, and perform a Mars gravity assist into the asteroid belt. Next, use tether assists with several main belt asteroids in succession to gain the velocity required to reach out to Jupiter. By using Mars, lower relative velocities of the spacecraft with each asteroid will be needed, and hence a lighter tether may be used than with a single intermediary asteroid. We believe that in most of these applications all or a major part of the tether is reuseable. This is one advantage of using a tether compared with using rocket propulsion and expending fuel.

Similar scenarios for tether assist missions may be developed for the other outer planets. It should be remembered, however, that Jupiter remains the most powerful source for gravity assist in the solar system.

Main Belt Asteroid Missions

The asteroid belt itself is the natural place for tether assist missions. As mentioned for the Jupiter mission, the spacecraft may utilize a Mars gravity assist to get from Earth into the asteroid belt. One can then imagine a spacecraft collecting samples of asteroid material at the same time it is performing a tether assist to fly on to another asteroid. After a tour of a number of asteroids, the process could be reversed by performing a gravity assist at Mars to return to Earth with the asteroid samples collected.

Main belt asteroid tours have been seriously considered using low-thrust rocket propulsion.[11] Successive rendezvous with from 4 to 8 asteroids would take up to 10 years. Although penetrators were suggested for in situ measurements, sample returns were not considered. Perhaps the ideal spacecraft to explore the asteroids in the main belt would use both low thrust and tether assist. With thrust, midcourse corrections could be made and the relative velocities at the asteroids could also be reduced to values where conventional materials would be adequate for a tether assist.

It is not known how many small asteroids (but still large enough for a tether assist) there may be in the main belt, since Earth-based telescopes cannot detect bodies smaller than about 1 km in diameter at that distance. There are probably more than a billion greater than 10 m in diameter with a mass greater than 1000 tons each, adequate for our method. In that case, the complete mission need not be preplanned based on knowledge of the position and orbits of selected asteroids that it should encounter. Instead, a spacecraft, thrust into the asteroid belt, could be capable of detecting 10-m asteroids at an adequate distance; for example, with passive optical sensors, backed up by ranging lasers once an object is detected. Then it would be determined whether the spacecraft can maneuver into position for a close flyby and perhaps a tether assist. In this manner, successive hops could be made with relatively little propulsion yet adding up to a considerable total velocity increment. No detailed analysis has been done on this unique mission as yet.

Finally, tethered assists may be valuable in the far future for possible economic utilization of asteroidal materials in space. It may, for example, be necessary to return asteroidal mass to the vicinity of the Earth or Moon on a continuing basis. Rather than expendable propellants, a set of permanent reuseable tether stations on a string of asteroids could provide the means to transport the mined material back to Earth.

Conclusions

An alternate method of producing gravity assist using asteroids has been presented. Successful development of this technique will depend on many factors, some of the more important being: higher-strength tether material, a method of attaching and releasing a tether with an asteroid, tether dynamics control, and development of a navigation system to achieve the required accuracies for tether attachment and release.

Even when these problems have been solved, actual use of the system will be heavily mission-dependent. Tradeoff studies will be required to decide whether the tether system or conventional rocket propulsion or some combination of both is optimum for the mission goals. Tethers appear to have significant merit in missions where they can be reused several times. For highly repetitive use they may be the only practical devices.

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