THE STATITE: A NON-ORBITING SPACECRAFT

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Abstract

In this paper I describe a completely new type of space vehicle, called a "statite"--a spacecraft that does not orbit. The statite can be used for placing and maintaining a space services system so it is continuously viewable from either the north or south hemisphere of Earth, yet it does not take up space on the crowded equatorial geosynchronous orbit. To properly appreciate the statite concept, it is important to realize that all of the thousands of space objects presently in orbit around the Earth use the centrifugal force generated by their orbital motion to balance the Earth's gravitational force. In contrast, the statite is a space object that does not use centrifugal force from orbital motion about the Earth to counteract any significant portion of the Earth's gravitational force. Instead, the statite uses a solar sail propulsion system to maintain the statite and its payload in a desired non-orbiting static position adjacent to the Earth by balancing light pressure force against the Earth's gravitation force. In most versions of the system, the statite is offset from the polar axis toward the dark side of the Earth. The statite stays fixed at a point above the dark side, while the Earth spins beneath it. The statite can be placed anywhere over a large area on the dark side of the Earth. This is in contrast to the single linear arc of the equatorial geostationary arc. From the viewpoint of an observer on the rotating Earth, this version of the statite rotates around the pole once every 24 hours (a solar day). Thus, ground stations for communication with these statites must have their antennas on a polar mount with a 24 hour clock drive. Since the distance between the ground station and the statite does not change significantly in magnitude, and the doppler shifts are very low, the electronics needed for these versions of the system are nearly as simple as those at the fixed position ground stations. A typical distance of a statite from the center of the Earth is 30 to 300 Earth radii. The better the performance of the sail, the closer the balance point. (For reference, geostationary orbit is at 6.6 Earth radii and the Moon is at 63 Earth radii.) The round-trip delay time for 100 Earth radii is 4.2 seconds. The advantages of the statite concept are: it provides continuous service to a region using a single spacecraft without requiring a slot on the crowded equatorial geostationary orbit, and it provides continuous coverage to regions of the Earth that are too close to the poles to use the existing equatorial geostationary orbit satellites. The disadvantages of the statite concept are: constant control is required to maintain station, larger antennas will be needed because of the greater communication distance, the round-trip communication time is in seconds, and in most versions the ground station antenna must rotate once a day.

Background

The scientific possibility of launching a device so it remains in orbit around the Earth was first mentioned by Newton in the Principia.[1] He imagined a mountain so high that air no longer interfered with the motion of a projectile. As shown in Figure 1, a projectile, shot horizontally from the top of the mountain, would fall to the Earth at some distance.

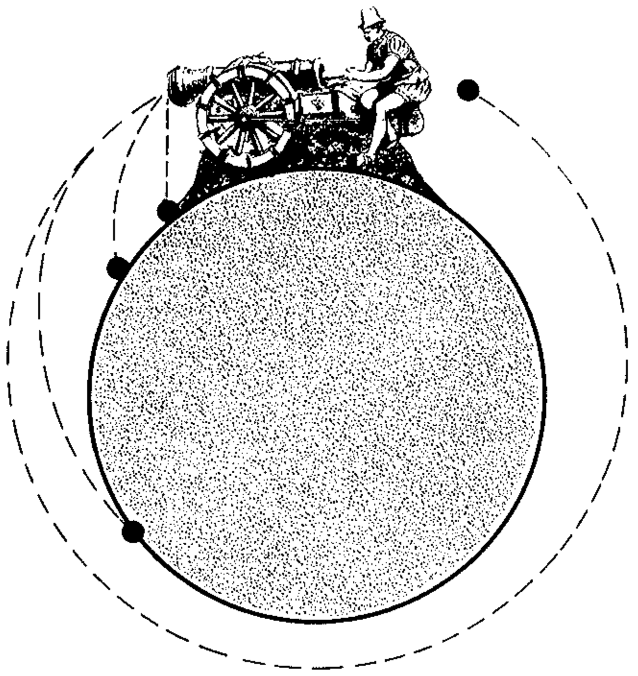

Fig. 1 - Newton Explains Trajectories and Orbits

If the speed of the projectile was increased, the trajectory would flatten out and the projectile would fall to Earth further away. Eventually, if the projectile was give a velocity such that the curvature of its trajectory coincides with that of the Earth's surface, the projectile would go entirely around the Earth and continue to circle it. Newton used this imagery to show that the gravitational laws governing the motion of celestial bodies would also apply to a body ejected from the Earth and circling it in the vacuum of outer space at a velocity high enough that the centrifugal and gravitational forces balanced. Two and a quarter centuries later, on 4 October 1957, Newton's concept was realized by the launch of Sputnik 1. Since the launch of Sputnik 1, thousands of artificial space objects have been placed in orbit around the Earth.

Satellites are placed into various orbits for different tasks. The purpose of these orbits is to allow the satellite to remain adjacent to the Earth so it will be useful for some purpose. For example, it is desirable that communications satellites remain stationary over a single point of

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the Earth's surface. This allows the ground stations used for receiving signals from the communications satellites to use simple fixed parabolic antennas that point in a single direction. The laws of orbital mechanics provide only a single orbital arc, called the geostationary orbital arc, where the orbital period of a satellite is the same as the rotational period of the Earth. The geostationary orbital arc is situated over the Earth's equator, at a distance of about 42,000 kilometers from the center of the Earth (36,000 kilometers from the surface). A satellite placed in this geostationary orbital arc will remain fixed over a single spot on the Earth's equator, as if it were at the top of a tall tower.

The fact that there is only one such orbital arc, and it is uniquely useful for communication, broadcast, weather, and other service satellites, creates a limited resource -- the positions along the orbital arc. Access to this limited resource is controlled by an international organization, the International Telecommunications Union (ITU).[2,3] Allocation of positions or "slots" along the geostationary orbital arc is hotly debated by the World Administrative Radio Conference, which is an organ of the ITU. The geostationary orbital arc is most useful for communications between the points on the Earth that lie near the equator where the ground station antennas may point more or less toward the zenith.

However, because of local topography and high attenuation through the atmosphere at low elevation angles, geostationary satellites are relatively useless at high latitudes on the Earth near the polar regions. For the near polar regions it is necessary to use other types of orbits for communications. One example is the "molniya" orbit used by Soviet satellites. This orbit has an apogee at roughly geostationary altitude over the North Pole, while the perigee near the South Pole is only a few hundred kilometers. This orbit has an orbital period of twelve hours and requires three satellites to maintain continuous satellite presence within fifteen degrees of the zenith over the northern latitudes. Further, since the satellites do not remain motionless in the sky, the ground stations must be equipped with complex tracking antennas and electronic receivers which add greatly to their cost.

Introduction

In order to reduce pressure on the geostationary orbital arc so as to relieve world tensions over this "limited natural resource" and, in addition, to provide continuous space services to the polar regions of the Earth, I propose the use of a new type of spacecraft. A spacecraft that does not orbit the Earth. Since the spacecraft does not orbit the Earth, it is not a satellite of the Earth. Indeed, the definition[4] of the word "satellite" is: "the lesser component of a two body system revolving, together with the primary, around a common center of mass". Since this type of spacecraft is not a satellite, I have coined the generic name of "statite"[4] for it, since it remains essentially static or stationary in space with respect to the center of mass of the combined system of the Earth and statite.

To properly appreciate the statite concept, it is important to realize that all of the thousands of space objects presently in orbit around the Earth fall in an essentially closed trajectory around the Earth under the influence of gravity. Although the satellites may carry a small reserve of fuel to alter their orbital trajectory, all space objects currently adjacent to the Earth spend the vast majority of their existence freely falling such that the centrifugal force generated by their orbital motion exactly balances the Earth's gravitational force. In contrast, the statite is a space object that does not use centrifugal force from orbital motion about the Earth to counteract any significant portion of the Earth's gravitational force.

Instead, as is shown in Figure 2, the statite uses a solar sail light pressure propulsion system to maintain the statite and its payload in a desired non-orbiting fixed position above the north or south hemisphere of Earth by exactly balancing the Earth's gravitation force with light pressure force.

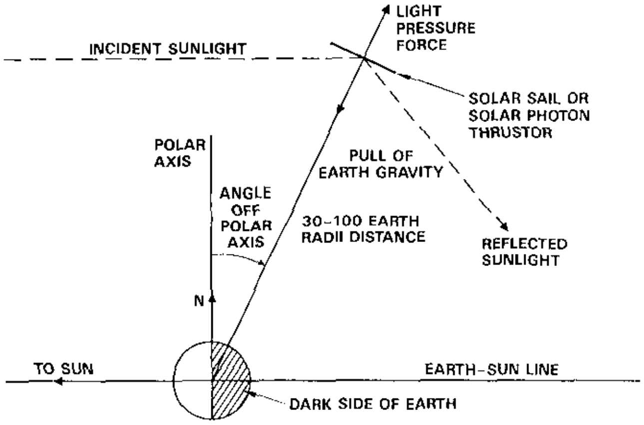

Fig. 2 - Schematic Diagram of Statite Concept

In some versions of the system, to be described later, the statite is kept directly over the North or South Pole of the spinning Earth. To an observer on the Earth, the statite stays fixed above the pole while the stars rotate around it. In these versions of the system, the ground stations can use fixed mounted antennas and simple fixed gain, fixed frequency electronics similar to that used in the ground stations for similar services supplied by satellites operating in the equatorial geostationary orbit.

In other versions of the system, the statite is offset from the polar axis. It stays fixed at a point above the dark side of the Earth, while the Earth spins beneath it. It should be noted that the statite does not have to be positioned directly opposite from the Sun. The statite can be placed anywhere over a large area on the dark side of the Earth. This is in contrast to the single linear arc of the equatorial geostationary orbit.

From the viewpoint of an observer on the rotating Earth, this version of the statite rotates around the pole once every 24 hours (a solar day). Thus, ground stations for communication with these versions of the statite systems must have their antennas on a polar mount with a 24 hour clock drive. Since the distance between the ground station and the statite does not change significantly in magnitude, and the doppler shifts are very low, the electronics needed in the ground stations for these versions of the system are nearly as simple as those at the fixed position ground stations for the equatorial geostationary satellites.

As will be shown later, the typical distance of a statite from the center of the Earth is 30 to 300 Earth radii. (For reference, geostationary orbit is at 6.6 Earth radii and the Moon is at 63 Earth radii.) Thus, one disadvantage of the statite system is that the round-trip delay time will be a number of seconds, making it more suitable for broadcast, data transmission, and weather services than two-way telephone conversations. For 30 Earth radii, the round trip delay time is 1.3 seconds, while for 100 Earth radii, it is 4.2 seconds.

Although the altitude of the statites will be comparable to the distance to the Moon, the statites will be above the polar regions of the Earth while the Moon will be above the equatorial regions. Thus, although the Moon will cause significant gravitational perturbations of the statite that will have to be handled by the statite control system, there is no danger of collision.

The basic advantage of the statite system over existing Earth services systems is that the statite can provide continuous service to any region of the Earth, including the polar regions, using only one space vehicle, and without requiring a position on the equatorial geostationary orbital arc.

Deployment and Operation

Since the operation of a statite requires the constant control of the thrust and direction of the light pressure propulsion system in order to keep the statite on station, the deployment and operation of a statite is significantly different from the deployment and operation of a satellite. Launching a satellite involves simply "throwing" it into space, where it will "float" in its elliptical orbit until it is commanded to move into a different orbit. A statite must be kept under active control at all times or it will soon fall to the Earth and be lost.

The statite will have some sort of Earth services payload, such as a standard two-way communications, one-way broadcasting, navigation, mapping, weather, or other surveillance system; a solar light pressure propulsion system such as a standard flat solar sail[6-11] or the improved performance Solar Photon Thrustor discussed in another paper[12] presented at this meeting; a sensing system capable of determining the direction to the Sun, the direction to a guide star off the ecliptic, such as Canopus, and the direction and distance to the Earth; and a control system that uses the output of the sensing system to automatically control the light pressure propulsion system to keep the statite at a desired position with respect to the center of the Earth.

The sensing system to determine the distance to the Earth could be a passive one that measures the angular diameter of the Earth with a rotating infrared sensor, or it could be an active one that picks up a radio signal from a cooperative station or stations on Earth and uses those signals to determine the range and range rate.

The statite would be launched by standard launchers either directly to the desired operating position, where the light pressure propulsion system is deployed, or to a low Earth orbit that is high enough that the propulsion system can be deployed and the statite "flown" into position using the light pressure propulsion system. Since the final velocity of the statite with respect to the center of the Earth during the operation of the system is essentially zero in most implementations, the direct placement maneuver involves a simple "pop-up" type launch, with considerable savings in fuel over a launch into an orbit at that same altitude. Once the statite is near its desired position and the light pressure propulsion system deployed, the sensing system acquires the Sun, Canopus, and Earth, determines the statite position with respect to the center of the Earth, then adjusts the light pressure propulsion system thrust level and direction to bring the statite to the desired position and maintain it there.

In some implementations, the light pressure propulsion system could be combined with a solar powered electrical power generation system that could provide much higher levels of onboard power than present solar cell systems. With proper design of the light pressure propulsion system, even the waste heat from the solar-electric conversion system could provide a component of propulsive thrust. This availability of large amounts of onboard electrical power would be advantageous for statites providing direct broadcast service.

When the statite is in its fixed position with respect to the center of the Earth, the sum of the gravitational forces from the Earth and Sun, and the centrifugal force from the orbiting of the Earth about the Sun, will attempt to pull the non-orbiting statite off position. (The usual result being that the statite will start to fall down toward the Earth.) The statite then uses the light pressure force from the sunlight to cancel out the sum of the gravitational and inertial forces and remain balanced at the desired fixed position with respect to the center of the Earth. This fixed point can be at any position around the spinning Earth, although positions over the dark side of the Earth result in lower statite altitudes for a given level of performance of the light pressure propulsion system.

Force Balance Analysis

The basic force diagram for the simplest version of the statite system is shown in Figure 3.

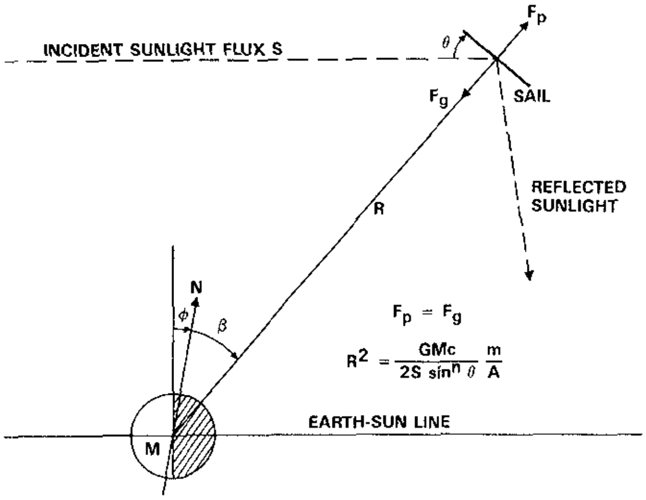

Fig. 3 - Statite Force Diagram

For simplicity, the light pressure propulsion system is shown as a flat solar sail. In practice, however, it is likely that an improved light pressure propulsion system, called the Solar Photon Thrustor[12] will be used. In Figure 3, the plane of the diagram is not normal to the plane of the ecliptic, but has been rotated about the Earth-Sun line until the polar axis is in the plane of the paper. In Figure 3, the North Pole of the Earth is tilted at an angle ϕ with respect to the terminator (the shadow line around the Earth), which is normal to the Earth-Sun line. The angle ϕ is due to the tilt of the polar axis of the Earth with respect to the ecliptic and varies from ±23.5° during the year.

The statite is placed at a distance R from the Earth at an angle β with respect to the polar axis, in this example, the North Pole. For simplicity, we have assumed in Figure 3 that the statite is also in the plane of the paper. In general, this will not be the case, as the statite can be anywhere over the dark side of the Earth and does not have to be exactly on the opposite side of the pole from the Sun. The sail on the statite is then oriented tangent to the radial direction to the Earth. The light from the Sun strikes the reflective sail at an angle Θ. Simple geometric considerations will show that $\Theta=\beta+\phi$ when the statite is directly opposite the pole from the sun.

The sunlight reflecting off the sail produces a light pressure force F_p. If the flat solar sail is highly reflecting (which is relatively easy to achieve in practice), then the direction of the light pressure force is normal to the back of the sail. Since the sail is tangent to the radial direction, and the light pressure force on a flat solar sail is normal to the back of the sail, the light pressure force will be directly away from the Earth. The magnitude of this light pressure force for a flat solar sail is given by the well-known relation:[7]

$$F_p = 2 \sin^2\Theta \ (SA/c) \qquad (1)$$

Where S is the solar flux, which at the Earth is 1.4 kW/m^2, A is the area of the solar sail, and c=300 Mm/s is the speed of light.

If a Solar Photon Thrustor,[12] shown schematically in Figure 4, is used instead of a flat solar sail, the net thrust direction would be adjusted to also be directly away from the Earth. For this type of solar light pressure propulsion system, the magnitude of the light pressure force is improved by a factor of $1/\sin\Theta$ over a flat solar sail:[12]

$$F_p = 2 \sin \Theta \ (SA/c) \qquad (2)$$

Where A is now the area of the collector portion of the Solar Photon Thrustor.

The gravitational force F_g of the Earth of mass M on a statite of mass m at the radial distance R is:

$$F_g = GMm/R^2 \qquad (3)$$

Where $G=6.67\times10^{-11}\ m^3/kg\cdot s^2$ is the Newtonian gravitational constant.

In the operation of a statite, the gravitational pull of the Earth is counteracted by the light pressure force:

$$F_p = F_g \qquad (4)$$

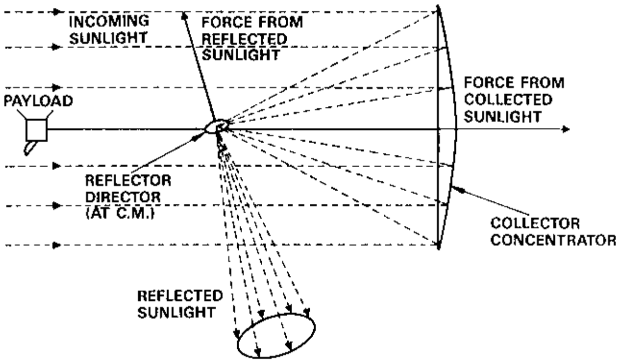

Fig. 4 - Solar Photon Thrustor Concept

Substituting equations (1), (2), and (3) into (4) gives:

$$2 \sin^n\Theta \ (SA/c) = GMm/R^2 \qquad (5)$$

Where n=2 for a flat solar sail and n=1 for a Solar Photon Thrustor.

If we solve equation (5) for the equilibrium distance R of the statite from the center of the Earth, we obtain:

$$R^2 = \frac{GMc}{2S \sin^n\Theta} \ \frac{m}{A} \qquad (6)$$

Where m/A is the effective total mass-to-area ratio of the statite.

Substituting in values for the various constants and using the values for the solar flux at the Earth and the Earth mass, equation (6) reduces to:

$$R^2 = \frac{4.3\times10^{19}\ m^4/kg}{\sin^n\Theta} \ \frac{m}{A} \qquad (7)$$

The square root of Equation (7) is plotted in Figure 5 for the two different types of light pressure propulsion systems, as a function of mass-to-area ratio and incoming solar flux angle Θ. We can see that the statite altitudes vary from approximately 30 to 300 Earth radii, with the operational altitude decreasing as the performance (in terms of total spacecraft mass to sail area) of the solar sail system improves. The round trip communications time delay of these systems will always be greater than one second, making them more suitable for broadcast and Earth monitoring than as telephone communication satellites. We can also see that the Solar Photon Thrustor type of sail gives significantly improved performance over a flat sail for operation close to the poles, where the effective sun angle is small.

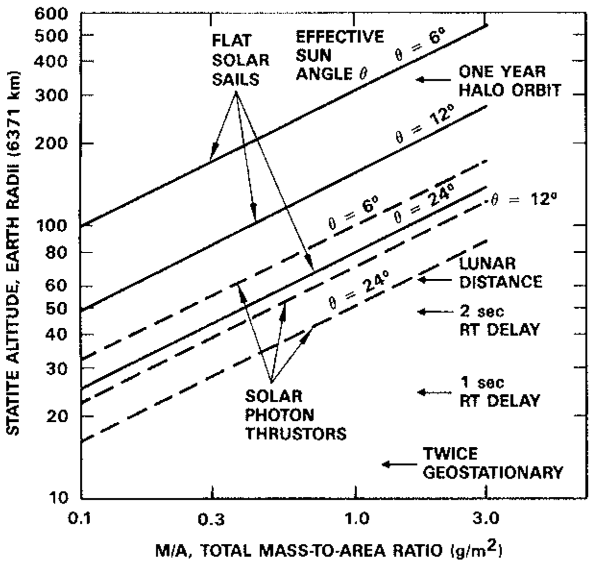

Fig. 5 - Statite Altitude for Various Systems

Performance Estimates

To give some estimate of what could be accomplished in a first generation version of a statite, we will assume a sail or light collector built using the technology studied in detail by JPL in 1976.[8,9] The mass per unit area (m/A) of their design was 3.3 gm/m². Substituting this value into equation (7) produces:

$$R^2 = \frac{1.4\text{x}10^{17}\ \text{m}^2}{\sin^n\Theta} \qquad (8)$$

If we put this in terms of Earth radii $R_\oplus$ and take the square root, we get:

$$R = \frac{60\ R_\oplus}{(\sin\Theta)^{n/2}} \qquad (9)$$

Since $\sin\Theta<1$, this means that the minimum distance from the Earth for a statite using 1976 sail technology is 60 Earth radii or about 9 times geostationary orbit distance. Second and third generation sail and reflector technology will have smaller mass-to-area ratios and will allow the statites to operate at lower altitudes and at angles closer to the poles.

If a second generation flat solar sail is made with a total mass-to-area ratio of 1.0 g/m², and used at a fixed polar angle of 47.5° off from the north polar axis, then the worst Sun angle Θ will be 47.5°-23.5°=24° at the Summer Solstice. Looking up a flat solar sail at m/A=1.0 g/m2 and Θ=24° in Figure 5 gives a statite altitude of 80 Earth radii. The statite can be kept at that altitude during the year by decreasing the thrust level.

If a third generation Solar Photon Thrustor[12] is made with a total mass-to-area ratio approaching that of Drexler's high performance solar sail designs[11] of 0.1 g/m² and used as a fixed polar angle statite at 35.5° off from the north polar axis, then the worst Sun angle will be 12° at the Summer Solstice. In Figure 5, a Solar Photon Thrustor with m/A=0.1 g/m² and Θ=12° has an altitude of 22.5 Earth radii and a round trip delay time of less than 1.0 sec. The statite could be lowered in altitude during the rest of the year to the point where the time delay becomes comparable to that experienced with equatorial geostationary communication systems, especially longer circuits where double bounces between Earth and orbit occur.

Modes of Operation

Depending upon the operational requirements, the statite system can be operated in a number of modes. These modes of operation include the fixed polar angle mode, variable position mode, a mode involving "formation flying" with the Earth in a levitated solar orbit, and a "halo" orbit mode.

Fixed Polar Angle Mode

In the normal mode of operation the statite is always kept at a fixed angle from the polar axis. This angle will have to be greater than 23.5° because the tilt of the polar axis of the Earth takes each pole 23.5° to the sunward side of the Earth during one of the solstices and the statite has to stay over the dark side.

As is shown in Figure 6, the worst case for a statite serving the northern hemisphere comes at the Summer Solstice, when the polar axis angle with respect to the terminator is ϕ=-23.5°. In this case, the closest an ideal statite can come to the polar axis is 23.5°, and realistic statites will be at angles of 30° to 45° from the polar axis. Statites at these angles could provide services to the United States, Europe, Alaska, Canada, all of the USSR, Northern China, Argentina, Chile, New Zealand, Southern Australia, and, of course, the Arctic and Antarctic, which cannot use satellites on the equatorial geostationary orbital arc at all.

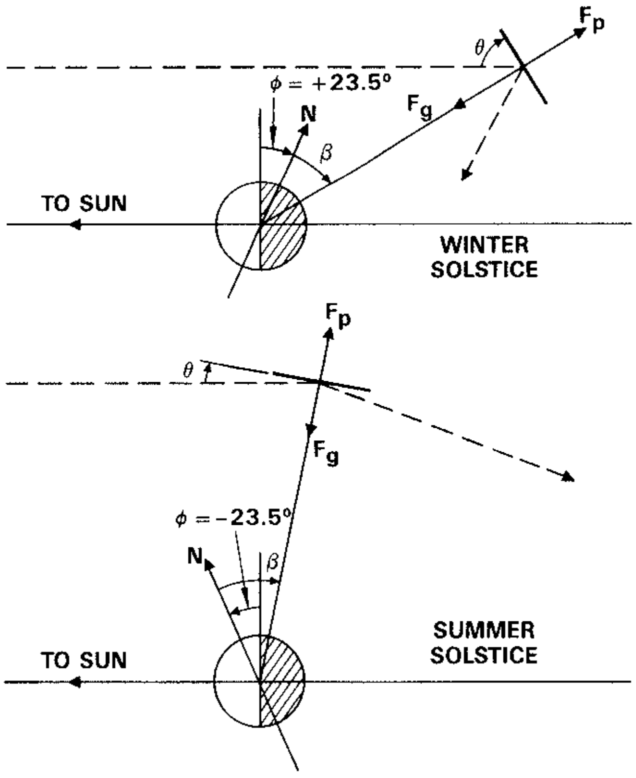

Fig. 6 - Fixed Polar Angle Operation of Statite

At a worst case example of Summer Solstice and an angle from the polar axis of $\beta=30^\circ$, the angle of the incoming sunlight will be $\theta=6.5^\circ$. At this "close-hauled" angle to the sunlight, the performance of the flat solar sail is severely degraded, since $\sin\theta=0.11$. Looking at equation (9), this means that for the flat solar sail the operational altitude is $1/\sin\theta=9$ times the minimum altitude for a sail with a given mass-to-area ratio. In contrast, the operational altitude for a Solar Photon Thrustor is only $1/(\sin\theta)^{1/2}=3$ times the minimum altitude if it has a light collector with a similar mass-to-area ratio. This shows the significant advantage of the Solar Photon Thrustor over the flat solar sail in providing service to the polar regions.

Variable Position Mode

Instead of keeping the statite at a constant angle from the polar axis and a constant distance from the center of the Earth, another mode of operation would be to keep the statite as close to the polar axis as possible. The statite would be put directly over the pole during that time of the year when the polar region being served is on the dark side of the Earth (around the Winter Solstice for the North Pole), so as to provide maximum service area. During the Summer, when the North Pole is in sunlight and there is an unfavorable Sun angle, the statite would have to be moved off the polar axis position. This mode of operation would require more complicated ground station antennas capable of nodding once per year in addition to rotating around the pole once per day, and service to the more equatorial areas would be interrupted during some times of the year. A version of this mode of operation would be to allow the statite to drift higher in altitude at unfavorable Sun angles in order to lower the gravitational force and allow the statite to be operated a few degrees closer to the zenith.

Formation Flying Mode

A very different mode of operation of the statite system is possible that would allow the statite to be placed at <u>any</u> point around the Earth (specifically over the <u>poles</u>), at <u>all</u> times of the year, even over the <u>sunlit</u> side, at the expense of a slightly greater operating distance. Instead of the statite being balanced by sunlight in the gravitational field of the Earth, the statite would be placed in an orbit around the Sun, at such a distance from the Earth that the gravitational field of the Earth plus Moon is only a perturbation on the gravitational field of the Sun.

The propulsion system would then be controlled so that the statite traveled in a slightly elliptical orbit around the Sun with a period equal to the Earth orbital period of one year. The light pressure would be used to "levitate"[13] the plane of the statite orbit above or below the ecliptic plane, and to vary the radius of the orbit during the year so that the statite moved inside and outside the orbit of the Earth. The result would be that, to an observer on the Earth, the statite stayed fixed above one of the poles of the Earth. Thus, although the spacecraft is a "satellite" of the Sun, it is a "statite" of the Earth. This mode of operation is shown in Figure 7, showing the statite above the North Pole at the Equinoxes and the Solstices.

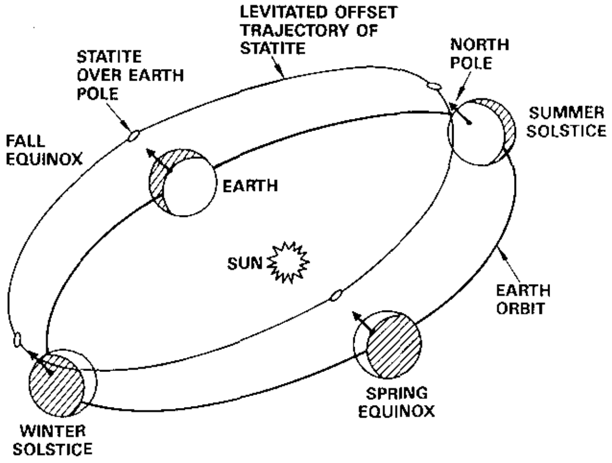

Fig. 7 - Solar Orbit Dominated Earth Statite

The major criteria for this mode of operation is that the perturbing gravitational forces of the Earth-Moon system be small compared to the gravitational force of the Sun. This occurs when:

$$GM_s/R_s^2 >> GM_e/R_e^2 \tag{10}$$

Where M_e and M_s are the mass of the Earth and Sun, and R_e and R_s are the distances from the statite to the Earth and Sun.

Solving equation (10) for the distance R_e of the statite from the Earth gives:

$$R_e >> (M_e/M_s)^{1/2} R_s \tag{11}$$

Putting in the mass of the Earth and Sun, and the distance from the Earth to the Sun for the average distance R_s between the Sun and the statite, we get:

$$R_e >> 260{,}000 \text{ km} = 40 R_\oplus \tag{12}$$

This shows that the gravitational field of the Sun and the Earth are the same magnitude at 40 Earth radii. Since the Earth is in orbit around the Sun, the centrifugal force due to the orbital motion is also of the same magnitude (and is cancelling the gravitational force of the Sun to first order).

Because the gravitational field of the Earth falls off as the square of the distance, a factor of three increase in statite altitude, or an statite distance of 120 Earth radii, would make the Earth's field about 10% of the Sun's field. For statite operational distances greater than that, the motion of the statite would be determined predominantly by its orbit around the Sun, as deliberately modified by the constant thrust from the light pressure propulsion system.

The control exerted by a light pressure propulsion system on its orbit around a light source like the Sun is determined by its "lightness" L, or the ratio of the light pressure force to the gravitational force:

$$L = \frac{2AS_oR_o^2/cR_s^2}{GMm/R_s^2} \tag{13}$$

Where R_o is the distance of the Earth from the Sun, and S_o is the solar flux at the Earth. Notice that since the light flux from the Sun and the gravity force from the Sun both fall off with the square of the distance R_s of the light pressure propulsion system from the Sun, the lightness is independent of the distance from the Sun and is predominantly determined by the mass-to-area ratio of the light pressure propulsion system.

A lightness of unity means that the light pressure propulsion system can levitate itself in the light from the Sun. Spacecraft with a lightness less than less than unity have to orbit the Sun to keep from falling in. For a light pressure propulsion system to achieve a lightness of unity requires a mass to area ratio of:

$$m/A = 2S_oR_o^2/GMc = 1.6 \text{ g/m}^2 \qquad (14)$$

Since the 1976 JPL sail technology projected a mass-to-area ratio of 3.3 g/m^2, any reasonable design for a light pressure propulsion system, whether it be a flat solar sail or a Solar Photon Thrustor, should be close enough to a lightness of unity that it will have ample reserve propulsive capability to allow it to carry out the orbit levitation and orbit ellipticity maneuvers necessary to place a statite over the poles of the Earth at all times of the year using the modified solar orbit "formation flying" mode.

Halo Orbit Mode

A final mode of operation is called a HALOSAT system since the statite is not completely stationary with respect to the center of the Earth. Although the statite is moving, it is not in orbit around the Earth, and therefore is not a satellite of the Earth. The structure of the HALOSAT spacecraft is the same as the statite spacecraft, only the operation is different. As is shown in Figure 8, if a statite keeps its orientation inectially fixed while it is displaced off its normal fixed operating point, the light pressure force F_p will compensate the component of the gravitational force F_{gz} normal to the sail, but there will be a component of the gravitational force F_{gr} tangent to the sail that will attempt to pull the statite back to the normal fixed operating point, as if there were a mass at that point. The disturbed statite can either oscillate back and forth through that point, or circle in a "halo orbit" around that point.

In Figure 8, the statite is orbiting in a circle of radius r at an angular velocity Ω. The plane of the halo orbit is tangent to the Earth, while the center of the halo orbit is the normal fixed operating point of the statite if it were not in a halo orbit. Equating the gravitational centripetal force tangent to the sail with the centrifugal force of the "orbital" motion gives:

$$GMmr/R^3 = m\Omega^2 r \qquad (15)$$

Note that both the mass of the spacecraft and the radius of the orbit cancel out of equation (15). These halo orbits are driven only by the gravity gradient of the Earth at that altitude and the orbital period of the HALOSAT is independent of the radius of the halo orbit:

$$\Omega^2 = GM/R^3 \qquad (16)$$

(Note that if R is large enough, the mass M should include the mass of the Moon as well as the Earth.)

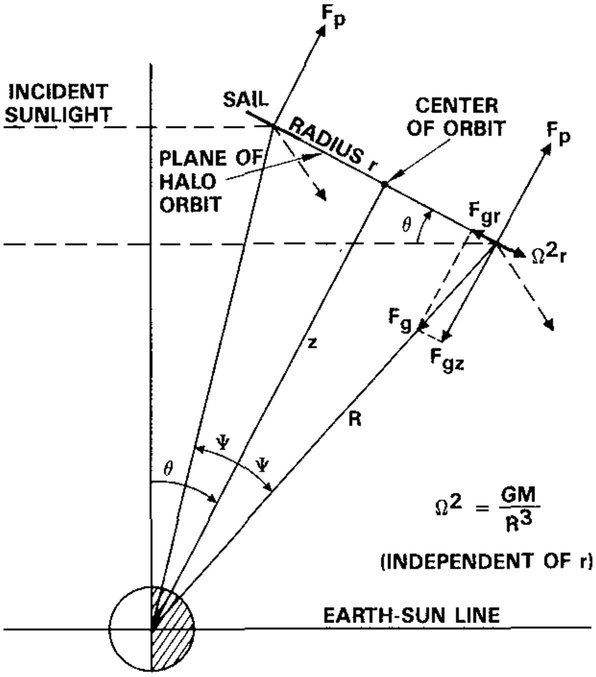

Fig. 8 - Force Diagram of Halo Orbit

There is an interesting distance of 340 Earth radii, where the period of the halo orbit is one year. The Earth gravity at this distance is so weak that it could be easily reached by a 1976 JPL sail carrying a 5 ton payload and having a resultant mass-to-area ratio of 10 gm/m^2. The center of the halo orbit would be chosen at some distance over on the dark side of the Earth that would give a comfortable sail tilt angle θ and plenty of light pressure force. The radius of the halo orbit would be chosen so that the angle ψ in Figure 8 were equal to θ. If the phase of the orbit were adjusted so that the HALOSAT started out over the northernmost portion of the terminator when the polar axis were tilted toward the Sun, the HALOSAT would be above the Arctic Circle, 23.5° away from the polar axis, where the terminator and Arctic Circle just touch. During the year, as the Earth goes around the Sun, the HALOSAT, with its one year period, will circle around above the Arctic Circle, keeping itself positioned over that point where the northernmost portion of the terminator crosses the Arctic Circle. To an observer on the ground it will spin around the pole once a day, staying on the opposite side of the Earth from the Sun. With an angle of 23.5° from the polar axis and its large distance of 340 Earth radii, the one-year HALOSAT can be seen anywhere north of 24° latitude.

Summary

I have proposed the use of a new type of spacecraft, called a statite. Unlike a satellite, the statite does not orbit the Earth. Instead of cancelling the gravitational pull of the Earth by using centrifugal force from orbital motion, the statite uses light pressure force from a solar sail.

The statite can be used for placing and maintaining a space services system so it is continuously viewable from either the north or south hemisphere of Earth, yet it does not take up space on the crowded equatorial geosynchronous orbit. In most versions of the system, the statite is offset from the polar axis toward the dark side of the Earth. The statite stays fixed at a point above the dark side, while the Earth spins beneath it. From the viewpoint of an observer on the rotating Earth, the statite rotates around the pole once every 24 hours (a solar day). Thus, ground stations for communication with these statites must have their antennas on a polar mount with a 24 hour clock drive.

A typical distance of a statite from the center of the Earth is 30 to 300 Earth radii. The better the performance of the sail, the closer the balance point. (For reference, geostationary orbit is at 6.6 Earth radii and the Moon is at 63 Earth radii.) The round-trip delay time for 100 Earth radii is 4.2 seconds.

The advantages of the statite concept are that it provides continuous service to a region using a single spacecraft without requiring a slot on the already crowded equatorial geostationary orbit, and it provides continuous coverage to regions of the Earth that are too close to the poles to use the existing equatorial geostationary orbit satellites. The disadvantages of the statite concept are: constant control is required to maintain station, larger antennas will be needed because of the greater link distance, the round-trip link time is in seconds, and in most versions the ground station antenna must rotate once a day.

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