

# The orbital tower: a spacecraft launcher using the Earth's rotational energy

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(Received 17 September 1974; revised 27 January 1975)

**Abstract**—The theoretical possibility is examined of constructing a tower to connect a geostationary satellite to the ground. The "orbital tower" could be built only by overcoming the three problems of buckling, strength, and dynamic stability. The buckling problem could be solved by building the tower outward from the geostationary point so that it remains balanced in tension and stabilized by the gravity gradient until the lower end touches the Earth and the upper end reaches 144,000 km altitude. The strength problem could be solved by tapering the cross-sectional area of the tower as an exponential function of the gravitational and inertial forces, from a maximum at the geostationary point to a minimum at the ends. The strength requirements are extremely demanding, but the required strength-to-weight ratio is theoretically available in perfect-crystal whiskers of graphite. The dynamic stability is investigated and the tower is found to be stable under the vertical forces of lunar tidal excitations and under the lateral forces due to payloads moving along the tower. By recovering the excess energy of returning spacecraft, the tower would be able to launch other spacecraft into geostationary orbit with no power required other than frictional and conversion losses. By extracting energy from the Earth's rotation, the orbital tower would be able to launch spacecraft without rockets from the geostationary orbit to reach all the planets or to escape the solar system.

## Introduction

A SATELLITE in equatorial orbit with a period of 24 hr appears fixed above a point on the equator, and is thus called a geostationary satellite. Since the altitude of this orbit is 35,800 km, a geostationary satellite can provide continuous communication over nearly half the earth. Arthur Clarke (1945) first proposed the geostationary satellite for world-wide communication, and many such satellites are now in orbit over various parts of the equator, carrying an increasing share of international communications.

The fixed position of the geostationary satellite with respect to the ground lends itself to more than an electro-magnetic signal connecting it to the Earth. If a physical connection could be made between the geostationary satellite and the ground, it would allow vertical ascent by powered capsules up this "orbital tower" directly into geostationary orbit. These capsules would be safer than rockets; in case of power failure, they could clamp onto the tower until repairs could be made. Satellites could be recovered by allowing them to slide down the tower to the ground. This method of returning satellites to the Earth would allow the recovery of their excess energy now wasted by heat shields. The use of this energy could greatly decrease the cost of launching satellites.

The problem of building the orbital tower is examined in this paper. A concept is proposed for the method of construction. The completed tower is analyzed statically as a thin rod in tension under gravitational and inertial forces. The dy-

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dynamic response to Moon-induced tidal excitations uses the same model. The dynamic response of the tower to moving payloads is calculated based on the free vibration modes of the tower considered as a wire with a variable tension.

### Tower concept

Three problems stand in the way of building the orbital tower. First, any tower 35,800 km high would seemingly buckle unless it were hundreds of kilometers in diameter. Second, even if it were prevented from buckling, the stress at the base due to the weight of the material above would apparently exceed the strength of any known material, and it would collapse. Third, if the tower elastic modes were in resonance with the tidal excitations of the Moon, they would be amplified and the tower would be destroyed. These problems have been overcome by the concept for constructing the tower presented in this paper.

Assume that a uniform tower reaching the synchronous orbit is to be constructed and its weight is to be found. The net weight of an increment  $dr$  of the tower at distance  $r$  from the Earth's center is the excess of the gravitational over the inertial force:

$$dF = (GM\rho A/r^2 - \rho Av^2/r)dr \quad (1)$$

where  $G$  is the gravitational constant,  $M$  is the mass of the earth,  $\rho$  is the density of the tower and  $A$  is its cross-sectional area, and  $v$  is the velocity at point  $r$  on the tower due to the Earth's rotation. This velocity increases linearly with distance from the Earth's center according to the relation  $v = v_s r/r_s$ , where  $r_s$ , and  $v_s$ , are the synchronous orbit radius and velocity. Using this relation and the fact that

$$GM = g_0 r_0^2 \quad (2)$$

where  $r_0$  and  $g_0$  are the Earth's radius and surface gravity, and the formula

$$v_r^2 = GM/r \quad (3)$$

for the velocity  $v$ , at radius  $r$  of a body in circular orbit about the Earth, the force on a length of tower  $dr$  is then

$$dF = \rho A g_0 r_0^2 (1/r^2 - r/r_s^3) dr. \quad (4)$$

Integrating this equation from  $r_0$  to  $r_s$ , gives the total weight of a uniform tower as 13.8% of its weight in a one-gravity field, assuming no deformation due to stress. Constructing this tower to synchronous altitude is therefore equivalent to building a tower 4900 km high in a uniform one- $g$  field. This decrease in the effective gravitational force to zero at the synchronous orbit thus lowers the strength requirement greatly, but it leaves the buckling problem untouched.

The buckling problem can be solved, however, by noting that only towers in

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compression can buckle, and then by building the orbital tower entirely in tension. This can be done by using the effect of the gravity gradient on a body in orbit. The part of the tower at the synchronous altitude has no net weight; it is in orbit. The tower below this point has less than orbital velocity and therefore experiences a net downward force. Conversely, if the tower extended above the synchronous altitude, the upper part would possess more than orbital velocity and would experience a net upward force. If the tower extended far enough above the synchronous altitude, the entire weight of the tower below this point could be overcome and the tower would then be entirely in tension, balanced about the synchronous altitude. This would have the effect of replacing the maximum compressive stress at the base by the same maximum stress in tension at the synchronous point. The tower would therefore not buckle.

To find the required height for a completely balanced tower, eqn (4) is set in the form

$$F = \int_{r_0}^{r_1} \rho A g_0 r_0^2 (1/r^2 - r/r_s^3) dr = 0 \quad (5)$$

and solved for the  $r_t$  for which the weight is zero ( $F = 0$ ). The value of  $r_t$  is found to be about 150,000 km, corresponding to an altitude of nearly 144,000 km. This distance is a characteristic of the Earth's radius, surface gravity, and period of rotation.

The balanced tower has a maximum tensile force at the synchronous balance point, and this tensile force decreases toward the ends. In order to minimize the weight of the tower, its cross-sectional area should be tapered as a function of the gravitational and inertial forces to maintain a constant stress. Using eqn (4) for the force on the tower at point  $r$ , the expression for the differential weight  $dW$  may be written as

$$dW = \rho g_0 r_0^2 (1/r^2 - r/r_s^3) A(r) dr \quad (6)$$

where  $A(r)$  is the area at point  $r$ . If the stress is set to a constant  $\sigma$ , then

$$\sigma dA = \rho g_0 r_0^2 (1/r^2 - r/r_s^3) A(r) dr. \quad (7)$$

If this equation is put into the form

$$\frac{dA}{A(r)} = \frac{r_0^2}{h} (1/r^2 - r/r_s^3) dr \quad (8)$$

where  $h = \sigma/\rho g_0$ , it can be integrated directly to find  $A(r)$ :

$$A(r) = A_s e^{(3r_0^2/2hr_s)(-r_0/r + r_0 r^2/2r_s^3)} \quad (9)$$

where  $A_s$  is the cross-sectional area of the tower at the synchronous point. The result is a tower with an exponential taper from a maximum at the synchronous

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point  $r_s$  to a minimum at the ground  $r_0$  and the top  $r_1$ . The height of the balanced tapered tower is the same as the uniform tower. Solving eqn (9) for the taper ratio  $A_s/A_0$  gives

$$A_s/A_0 = e^{(r_0/h)(1+r_0^3/2r_s^3-3r_0/2r_s)} = e^{0.776r_0/h}. \quad (10)$$

Equation (10) shows that the amount of taper required decreases rapidly with increasing  $h$ . This relation between the taper ratio and  $h$  has been plotted in Fig. 1. The parameter  $h$  has the dimension of length and is often called the specific strength. For the purpose of this paper,  $h$  will be called the characteristic height, because it is the height to which a constant-diameter tower of the material could be built in a uniform one- $g$  field without exceeding the stress limit of the material at the base.

Since the stress in the tower is due to its weight, the material used must have a high strength and a low density—that is, a high strength-to-weight ratio. Possible building materials can be classified by their characteristic heights,  $h = \sigma/\rho g_0$ , where  $\sigma$  is the allowable stress and  $\rho$  is the density. Theoretically the tower could be built of any material, by simply using a large enough taper ratio. Practically, however, the taper ratio required for normal structural materials is very large, resulting in an enormous area at the synchronous point for a reasonable area at the ends.

The characteristic heights of some building materials have been plotted versus density in Fig. 2. The values for the common structural metals vary with the alloy, but they are generally in the tens of kilometers. To build the orbital tower with a stainless steel with an  $h$  of 50 km, for example, the taper ratio required from eqn (10) is  $e^{99}$ , which is impossibly high. The orbital tower will require structural materials with much greater characteristic heights.

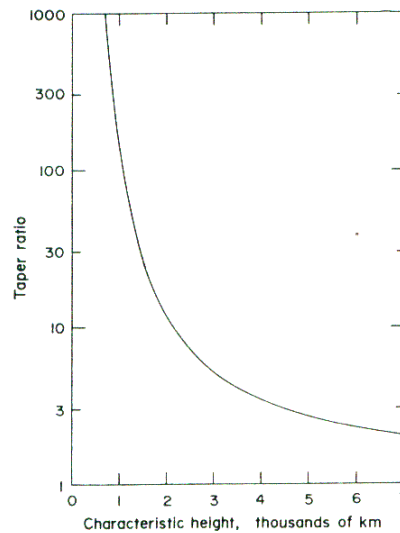


Fig. 1. Taper ratio required vs characteristic height.

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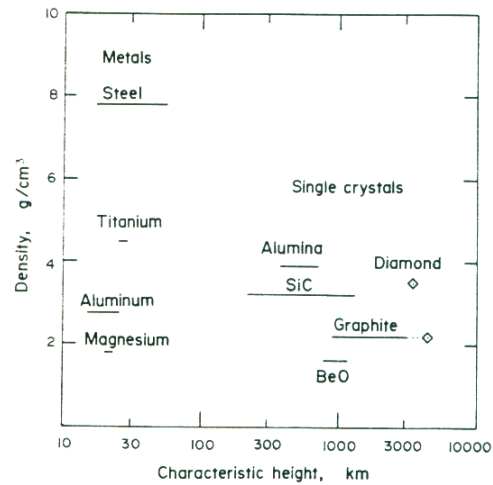


Fig. 2. Characteristic height vs density for various materials.

Some materials which promise characteristic heights of thousands of kilometers are the perfect-crystal whiskers that have been produced on a small scale (Levitt, 1970). The theoretical characteristic heights of diamond and graphite crystals are shown on Fig. 2 by symbols, based on a theoretical stress limit derived from the bond strength of single crystals (Mann, 1962). The laboratory observations of characteristic heights cover the range of values shown on the figure. Perfect crystals of graphite produce the highest observed values of  $h$ , from 900 to 3200 km. For  $h = 2150$  km, within this observed range, the taper ratio required to build the orbital tower is only ten. This means that the cross-sectional area at the synchronous point would have to be ten times the area at the ground. The tower would thus be able to withstand the required stress if it were tapered exponentially and built of these high-strength whisker materials. This design point of  $h = 2150$  km for perfect-crystal whiskers of graphite is based on a laboratory measurement of  $\sigma$  of  $46.5 \text{ GN/m}^2$ . The modulus of elasticity of these crystals is also subject to a large uncertainty, but one measurement is  $964 \text{ GN/m}^2$ , giving  $\sigma/E = 0.0482$  for a taper ratio of ten (Mann, 1962). For a taper ratio of thirty,  $\sigma/E = 0.0322$ .

### Tower construction

The orbital tower could be built in tension by constructing it outward from the geostationary orbit. The raw material could be carried into orbit by an advanced space shuttle and assembled there. An orbital construction module could be used, as indicated in Fig. 3. This module could be used as a geostationary space station after completion of the tower. The weightlessness and vacuum might even make space the logical place to produce the needed perfect-crystal graphite whiskers.

The balanced tower construction from geostationary orbit is further simplified in that the tower would be stable during construction. Since the long axis of the

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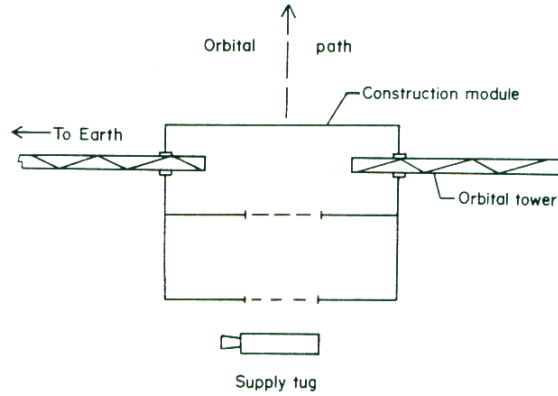


Fig. 3. Construction module for the orbital tower.

tower points toward the Earth, it would act as a gravity-gradient stabilized satellite. Figure 4 indicates the final length of the orbital tower in relation to the Earth and the Van Allen radiation belts, and also shows the variation in cross-sectional diameter as a function of the taper ratio. The variation in area could be accomplished by changing the thicknesses of hollow members while maintaining the external dimensions constant.

There are many engineering problems which could occur during the tower construction and anchoring, but none appears to be unsolvable. Orbital perturbations would be caused by geophysical and astronomical sources. If the tower were anchored at other than one of the stable nodes of the geostationary orbit, a slight daily drift in longitude would occur. Such perturbations would require that some care be taken in the final anchoring of the tower to the ground.

The lowest few kilometers of the tower would feel wind loads, but the required equatorial location of the tower base avoids the trade winds and the jet streams. According to Garbell (1947), the equator experiences very low average wind speeds; the jet streams are limited to temperature latitudes; and hurricanes never occur at less than  $5^\circ$  latitude. On the other hand, there are tropical tornadoes, and

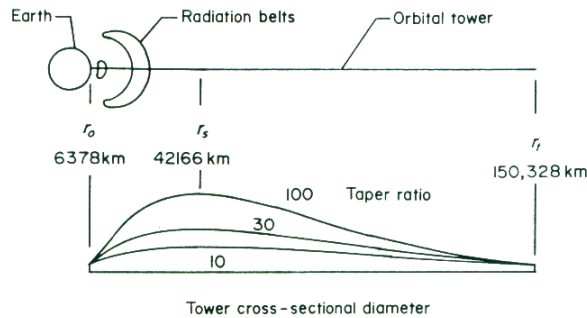


Fig. 4. The orbital tower and its cross-sectional diameter.

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the result of one passing through the tower would be an impulsive load. The peak velocity might be 150 m/s, giving a dynamic pressure of 8300  $N/m^2$ . If the tower had a minimum cross-sectional area of 50  $cm^2$  comprising three 10-cm radius cylinders, the total loading due to the wind would be 2500 N/m over perhaps 3000 m of tower length.

Wind loads of this magnitude would not be a problem, because of the large tensile strength reserve of the tower at the base. The reason for this is the truncation of the tower exponential taper at the Earth's surface. The cross-sectional area of the tower at any point is sufficient to support the weight of all the material below it. The part of the tower at the Earth's surface could thus support an imaginary extension of the tower to a zero diameter at the Earth's center. The actual tension in the tower at the Earth's surface is zero, because the exponential taper is truncated at this point. The increase in tension due to wind loads which could be supported is  $\sigma A(r_0)$ , or about  $2 \times 10^8$  N. To exceed this limit would require a much higher loading than that possible from a tornado. The tower thus appears to be immune to the vagaries of the weather. Even in the unlikely event that the orbital tower were severed near the base by a flying object, it would fail gracefully. The tower above the break would bend under the applied force, then return to its previous position. After the air resistance damped out the oscillation, the tower could be re-connected to the base. Since the tower itself is in orbit, there would be only infinitesimal motion of its center of mass.

Vertical vibration modes of the tower would be excited by the tidal forces of the Moon if their periods were 12.5 hr. To assess this problem the periods of several longitudinal vibration modes were calculated. Standard methods of analysis for a tapered rod in tension were used (Meirovitch, 1967). The assumption was made that the displacements, strains, and stresses are uniform at a given cross section, or that plane sections remain plane during deformation. This assumption is justified because the diameter of the tower is extremely small in relation to its length. The further assumption was made that the material remains in the linear portion of the stress-strain curve. Under these assumptions, the equation of motion is

$$\frac{\partial}{\partial r} \left[ EA(r) \frac{\partial u(r, t)}{\partial r} \right] = \rho A(r) \frac{\partial^2 u(r, t)}{\partial t^2} \quad (11)$$

where  $u$  is the vertical deflection from equilibrium. Substituting for  $A(r)$  from eqn (9) and assuming a constant  $E$ , the equation of the longitudinal motion is found to be

$$\frac{\partial^2 u}{\partial r^2} + \frac{1}{h} (r_0^2/r^2 - r_0^2 r/r_s^3) \frac{\partial u}{\partial r} = \frac{\rho}{E} \frac{\partial^2 u}{\partial t^2}. \quad (12)$$

Separation of the variables with  $u(r, t) = U(r)F(t)$  gives

$$\begin{aligned} \frac{d^2 U}{dr^2} + \frac{1}{h} (r_0^2/r^2 - r_0^2 r/r_s^3) \frac{dU}{dr} + \frac{\omega^2 \rho}{E} U &= 0 \\ \frac{d^2 F}{dt^2} + \omega^2 F &= 0 \end{aligned} \quad (13)$$

where  $\omega$  is the circular frequency. These equations were solved by using an analog computer to obtain the periods of vibration of the first six modes. An iterative process was used (Rogers and Connolly, 1960) based on the end conditions of  $U(r_0) = 0$ ,  $U(r_t) = U_0$  and  $U'(r_t) = 0$ , where the prime indicates the derivative with respect to  $r$ . The periods of the first few modes are plotted as functions of the taper ratio in Fig. 5. With a lunar tidal excitation period of 12.5 hr, there should be no amplification of any longitudinal vibration mode except for a taper ratio of three.

For the design point taper ratio of ten, the period of the longitudinal mode number one is seen from Fig. 5 to be 21.5 hr. Assuming that each mode responds as a single-degree-of-freedom system without damping, the first mode would experience an amplification factor of only 0.5 due to the tidal excitation. Smaller taper ratios would result in greater amplification, but they are probably not feasible because of the greater characteristic height required.

One other dynamic problem is the excitation of traveling waves along the tower by the transverse forces of payloads ascending the tower, analogous to the whipping of overhead electrical wires caused by the pantograph of a fast electric locomotive. There are critical velocities for which large oscillations would occur, corresponding to the velocities at which the payload would travel twice the length of the tower during one complete period of a lateral vibration mode (Timoshenko, 1941).

To assess this problem the periods of the first few lateral vibration modes were calculated. Since the tension in the tower is much greater than the Euler buckling load, the tower is assumed to vibrate as a wire in tension rather than as a beam. This assumption is surprisingly good, as will be demonstrated. Following Timoshenko (1955), the equation for the lateral vibration of a bar in tension is composed of two parts, one due to the restoring force of the tension and one due

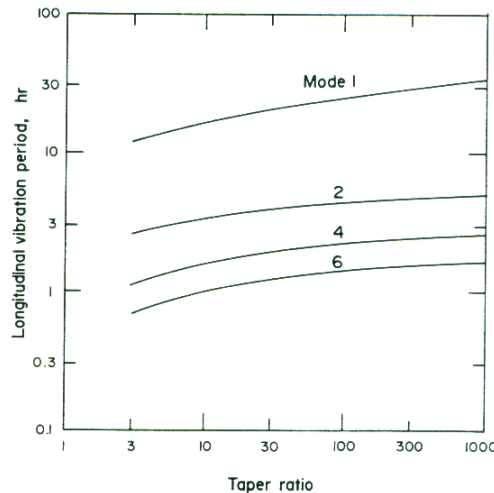


Fig. 5. Longitudinal vibration mode period vs taper ratio.



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to the bending stiffness. However, for a large tension and a small stiffness, as in a stretched wire, only the tensile restoring force need be considered. For the orbital tower, with an average width on the order of 10 m, the ratio of the length to the diameter is about fourteen million. The error in frequency caused by the assumption of a wire in tension is about  $10^{-5}$ , because the restoring force in tension divided by the restoring force in stiffness is proportional to the length squared. The bending stiffness of the orbital tower can thus be quite safely neglected. Summing the forces on an element of the tower gives the same form as eqn (11), with  $T(r)$  in place of  $EA(r)$ , where  $T(r)$  is the tension in the tower at point  $r$ . Assuming the tension at any point is  $\sigma A$ , the final equation in terms of the lateral displacement  $y(r, t) = Y(r)F(t)$  has the form of eqn (13):

$$\frac{d^2Y}{dr^2} + \frac{1}{h}(r_0^2/r^2 - r_0^2r/r_s^3)\frac{dY}{dr} + \frac{\omega^2\rho}{\sigma}Y = 0 \quad \frac{d^2F}{dt^2} + \omega^2F = 0 \quad (14)$$

These equations were solved in the same manner as eqns (13), with the end conditions  $Y(r_0) = 0$ ,  $Y(r_t) = Y_0$  (an arbitrary displacement), and  $Y'(r_t) = Y_0/r_t \approx 0$ . This latter condition means that at the free end of the tower there cannot be any transverse force. Since the tension is not zero near the end, the slope must parallel the tension. This direction is radially outward from the center of the Earth. For small oscillations, the ratio  $Y_0/r_t$  is essentially zero.

Based on these lateral vibration frequencies and the relation between them, the tower length, and the critical velocities,

$$v_n = 2f_n l \quad (15)$$

the first three critical velocities are shown in Fig. 6 as functions of the taper ratio.

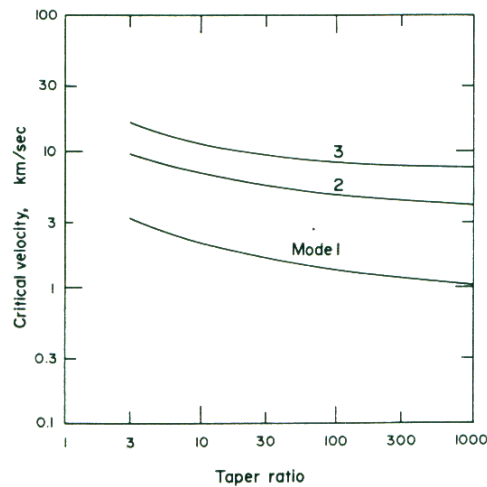


Fig. 6. Critical velocities vs taper ratio for moving payloads.

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Travel by payloads along the tower at these constant velocities would be prohibited, just as the critical speeds of drive shafts must be avoided. However, it would be permissible for a capsule to travel at a critical velocity for a few hours, before dangerous amplitudes could build up.

The foregoing analysis has assumed no tower elongation under load. Since the tensile force in the tower must necessarily be very high for a low taper ratio, there would be a definite elongation of the tower. The expression for this elongation is

$$\Delta = \int_{r_0}^r \frac{T(r)dr}{A(r)E} = \int_{r_0}^r \frac{\sigma}{E} dr = \frac{\sigma}{E}(r - r_0)$$

since  $T(r) = \sigma A(r)$ . This formula gives a good approximation to the elongation, but it does not take into account the change in force on each element of the tower when it is deformed. To do this, define  $y(r) = r + \Delta(r) = r + (r - r_0)\sigma/E$  and evaluate the integral

$$\begin{aligned} \Delta &= \int_{r_0}^y \frac{T(y)dy}{A(y)E} = \int_{r_0}^r \frac{\sigma}{E} \frac{dy}{dr} dr \\ &= \int_{r_0}^r \frac{\sigma}{E} (1 + \sigma/E) dr = \frac{\sigma}{E} (1 + \sigma/E)(r - r_0). \end{aligned}$$

Of course this small addition to the deformation will again increase the tension. In the limit, the total deformation is found by this iterative process to be

$$\frac{\Delta}{r - r_0} = \sigma/E + (\sigma/E)^2 + (\sigma/E)^3 + \dots$$

This series converges very rapidly. The result for a taper ratio of ten is a total elongation of 5.1%. A higher taper ratio would result in less elongation; for a taper ratio of thirty, the total elongation is 3.4%. The value of  $\sigma/E$  in these two cases is 0.0482 and 0.0322, respectively.

Such an elongation of the tower under stress would not change the shape, because each element has the same stress and therefore elongates by the same ratio. However, the location of the tower top would be changed. The exact height can be calculated from eqn (5) modified for elongation:

$$F = \int^y F(y)dy = \int^r F[y(r)] \frac{dy}{dr} dr = 0$$

where  $y = r(l + \Delta) - \Delta r_s$ , and  $F(y) = \rho A(y)g_0 r_0^2 (1/y^2 - y/r_s^3)$ .

Using the relation for  $A(r)$  from eqn (9), the equation for  $F$  can be set to zero and integrated. The result shows that for a taper ratio of 10, the tower length derived by eqn (5) would be increased by 15.4%; for a taper ratio of 30, the length would be increased by 8.6%. The effect of this elongation would be to increase slightly the periods of lateral vibration plotted in Fig. 5. The critical velocities of Fig. 6 would be unchanged, since the frequency decreases inversely with length.

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The major effect of allowing for the tower elongation is to make the orbital tower less susceptible to tidal resonance. The amount of elongation is reduced by using a higher taper ratio, which reduces the stress. The precise amount of the elongation is subject to change when better values of  $E$  for perfect-crystal whiskers are available.

A major difficulty in building the orbital tower is the immense volume of material needed. The amount of material is a function of the taper ratio and the minimum cross-sectional area of the tower base, as shown in Fig. 7 in terms of the volume of an untapered tower. The amount of material is also shown in terms of the number of launches required to orbit the material, assuming an advanced space shuttle with a capacity of  $300\text{ m}^3$  and a minimum tower area of  $50\text{ cm}^2$ . About 24,000 flights would be required for a taper ratio of 10, assuming that all the material were rocketed into synchronous orbit. The number of flights could be reduced by carrying most of the material up the tower itself after a minimum-diameter strand touched the ground. Nevertheless, the tremendous amount of material required means that the orbital tower would be by far the most demanding engineering project ever undertaken.

The preceding development has indicated that the orbital tower is theoretically possible; its practicality is another matter. The necessary ingredients include a highly advanced space shuttle with a payload perhaps thirty times that of the presently proposed shuttle; the perfection of techniques for growing the perfect-crystal graphite whiskers and enclosing them in a suitable matrix; and the development of a propulsion system for carrying payloads up the tower. The

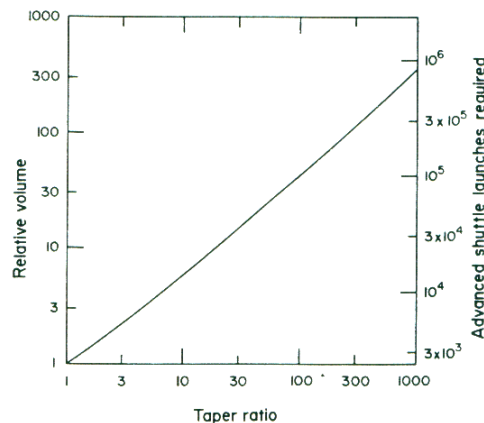


Fig. 7. Tower volume and advanced shuttle launches required vs taper ratio.

addition of propulsion and communication equipment to the tower and the necessity of allowing a proper safety factor to the allowed stresses would mean that a higher taper ratio would be required than shown for the theoretical values in Fig. 1; this would increase the required volume of material. Nevertheless, these needs can be met theoretically by choosing a taper ratio large enough.

### Tower uses

To justify its tremendous costs, the orbital tower has several unique attributes. The first is the potential for greatly reducing the energy required to launch geostationary satellites. The energy required for rocket launches may be summarized as the potential energy of the orbital radius and the kinetic energy of the orbital velocity. By sending a payload up the tower, the kinetic energy is saved; the tower imparts the orbital velocity automatically as the payload ascends. The saving is about 8% to geostationary orbit. This saving could be increased if the tower could be used as the conductor for a linear induction propulsion system (Thornton, 1973). By this method, a capsule ascending the tower would receive power through the tower itself, from a ground power station, or possibly from a solar power station located at the geostationary point (Patha and Woodcock, 1974). Conversely, a capsule descending the tower from orbit would be braked by having its excess energy absorbed electrically by the tower. By operating the capsules in pairs, one descending and providing energy to the tower and one ascending and absorbing energy from the tower, payloads could be orbited with greatly reduced energy. The net energy required would be only that portion used to lift into orbit the excess payload over that returning, plus frictional and conversion losses. Recapturing the energy of returning spacecraft would also end the need for heat shields.

The second important advantage of the tower is that it could be used to extract energy from the Earth's rotation by launching payloads from the geostationary altitude into higher orbits. At any point above the synchronous altitude the tower velocity is greater than orbital velocity; therefore, a payload released from the upper tower would attain a higher orbit. The velocity at the top of the tower is so great (10.93 km/s) that a payload released from there would escape the Earth without rocket propulsion. This velocity is sufficient to allow a probe to reach a solar distance of 12.3 or 0.26 astronomical units, depending on whether the probe is launched to augment or to diminish the Earth's orbital velocity. Probes released from the top would thus have sufficient velocity to travel as far from the Sun as Saturn or as far sunward as Mercury. These planets, Venus, Mars, and Jupiter would thus be accessible with no more energy than that required to reach the geostationary orbit. Since the tower's equatorial orbit is inclined to the ecliptic, trajectories out of the ecliptic plane would be possible in order to avoid the thickest part of the asteroid belt.

Even more energy could be extracted from the Earth's rotation by allowing the net outward force to accelerate a payload located above the synchronous altitude. If a payload were allowed to slide freely on the leading edge of the tower on a low-friction connection such as an air cushion, it would attain a large radial velocity as it moved upward. The net upward force is found from eqn (4) to be

$$F(r) = mg_0(r_0^2 r / r_s^3 - r_0^2 / r^2). \quad (16)$$

By the energy theorem, the final velocity is given by

$$\frac{1}{2}mv^2 = \int_{r_s}^{r_t} F dr = mg_0 r_0^2 \int_{r_s}^{r_t} (r / r_s^3 - 1 / r^2) dr. \quad (17)$$

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Substituting values and integrating gives a final radial velocity of 10.1 km/s at the end of the tower. This velocity, coupled with the tower tangential velocity, would allow the payload to reach all the planets past Saturn, and even to escape the solar system completely.

Figure 8 shows against the background stars the narrow band about the ecliptic which would be accessible to unpowered probes launched from the synchronous altitude on the tower. The maximum attainable hyperbolic excess velocity would be 13.8 km/s. By launching probes to pass near Jupiter and using Jupiter's gravitational field to increase the probe's heliocentric velocity, the accessible region could be greatly enlarged (Flandro, 1966). However, this would require the use of a powered stage with guidance, such as a Pioneer or Mariner spacecraft. A powered stage could also increase the accessible region directly by augmenting the tower launch velocity; but even unpowered probes could explore the neighborhood of the solar system beyond Pluto for the expected halo of comets and investigate the junction between the solar wind and the interstellar medium.

These results have been calculated based on the undeformed tower length. The effect of allowing for elongation of the tower due to the tension would be to increase the length somewhat for small taper ratios and to increase the launch capability correspondingly.

Any probe launched from the synchronous altitude would accelerate through the first two or three critical velocities of the tower, depending on the taper ratio, and the probe mass and its Coriolis acceleration would excite the tower lateral vibration modes. As a result, the probe mass would be limited by the allowable deflection of the tower. Fortunately, this is not a serious limit because the probe would pass through the critical velocities so rapidly that there would not be time for resonant amplitudes to build up. For example, from eqn (17) it can be derived that a probe launched from the synchronous point with a small initial velocity would require about 6 hr to reach the tower top. On the other hand, eqn (15) in conjunction with Fig. 6 shows that the first lateral mode has a period of about 30 hr. The excitation of this mode would then last only a small fraction of a cycle, producing little amplification.

The orbital tower has another interesting application, which is radioactive waste disposal. If the use of nuclear power plants continues to increase, so will the accumulation of radioactive wastes and the probability of an environmental

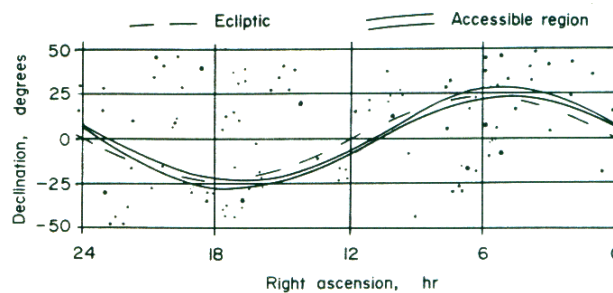


Fig. 8. Celestial region accessible to unpowered probes launched by the orbital tower.

disaster. One safe and permanent solution is to place these wastes into the ultimate incinerator, the Sun. If a small upper stage were added to a vehicle launched by the tower out past Saturn, this stage could be fired at aphelion to cancel the small remaining heliocentric velocity. The payload would then drop directly into the Sun, where its contents would be rendered completely harmless.

Other applications of the orbital tower might include the positioning of geostationary monitoring platforms at various altitudes and the experimental use of the orbital tower as a fixed conductor between the various radiation belts.

### Conclusions

The developments in this paper have indicated that it is theoretically possible to construct a tower connecting a geostationary satellite to the ground, if certain requirements are met. The orbital tower would be a gravity-gradient stabilized satellite itself, balanced in tension about the synchronous altitude and reaching to more than 144,000 km altitude. The tower material would require a strength-to-weight ratio equaled at present only by laboratory measurements of perfect-crystal whiskers. The tower would also require a very large volume of material to be carried into orbit. To construct a tower with a base cross-sectional area of  $50 \text{ cm}^2$  and a taper ratio of 10, about 24,000 flights would be required of an advanced space shuttle with thirty times the payload of the presently proposed shuttle.

The orbital tower could be used to launch probes without rockets from the synchronous altitude to all the planets or to escape the solar system, by extracting energy from the Earth's rotation. The tower could also be used to recapture the energy of returning spacecraft and use it to power other vehicles up the tower into orbit. This would require a linear induction propulsion system in the tower. By this method, the net energy cost of launching vehicles into geostationary orbit would be greatly reduced.

A simplified static analysis of the orbital tower and a dynamic analysis of its response to Moon-induced tidal excitations was performed, based on a model of the tower as a thin rod in tension and with small deflection. The results indicate that the tower would be stable for any taper ratio greater than 3. The dynamic analysis of the tower response to the forces of moving payloads, under the assumption of the tower as a wire in tension, indicates that there are critical velocities at which steady travel must be avoided. However, the tower vibration periods are several hours, so moderate acceleration through these critical velocities would prevent resonant buildup. Payloads launched from the geostationary point would accelerate rapidly enough to prevent large tower deflections.

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