

Oct. 6, 1970

C. J. SWET

3,532,298

METHOD FOR DEPLOYING AND STABILIZING ORBITING STRUCTURES

Filed Oct. 31, 1967

5 Sheets-Sheet 1

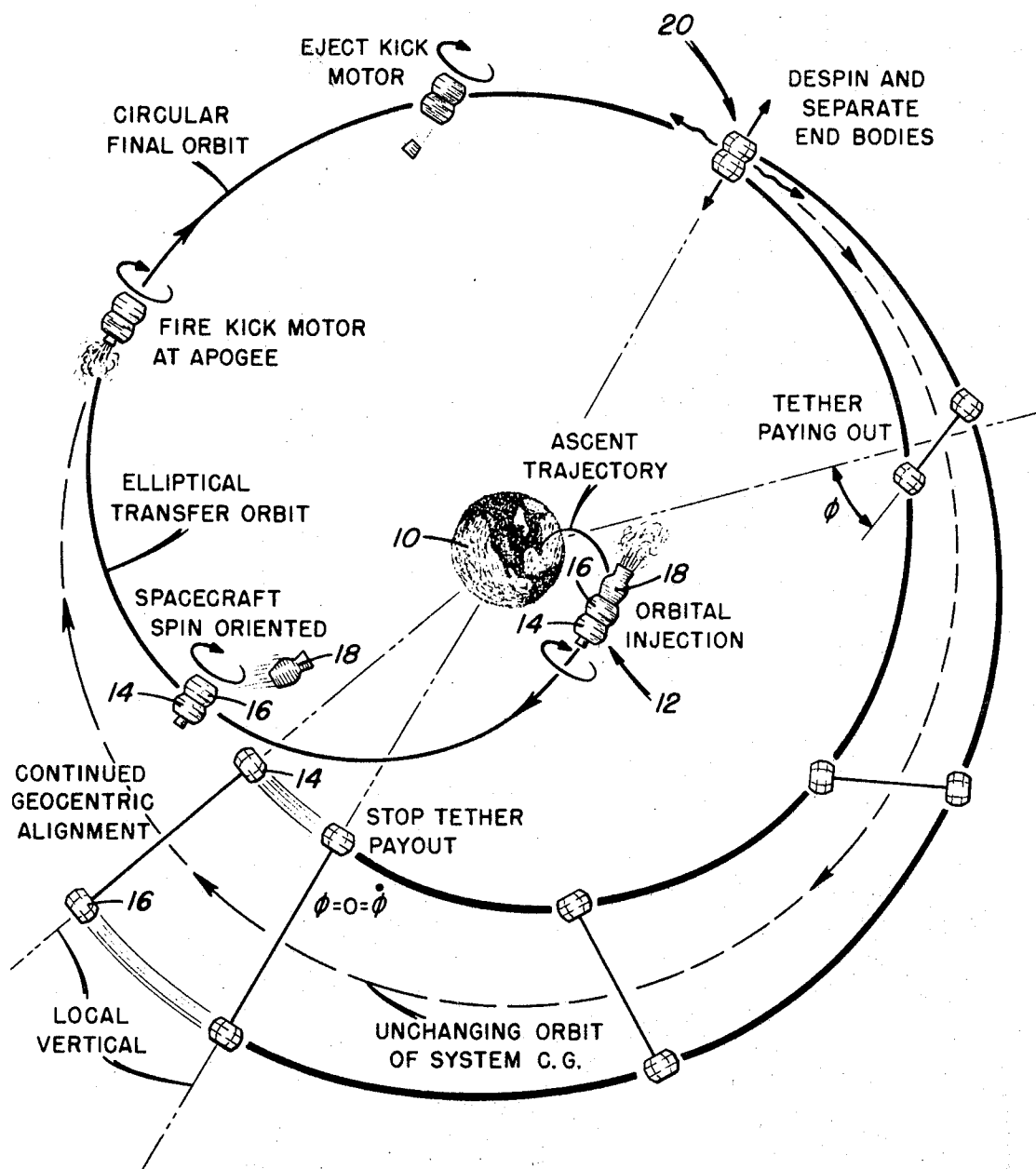


FIG. 1

CHARLES J. SWET
INVENTOR

BY

J. O. Treanor
ATTORNEY

Oct. 6, 1970

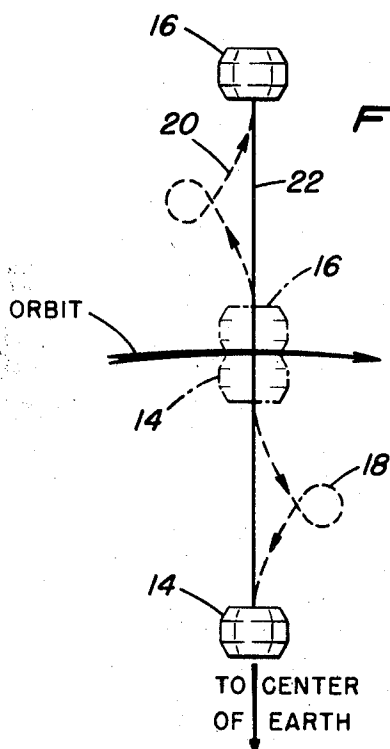
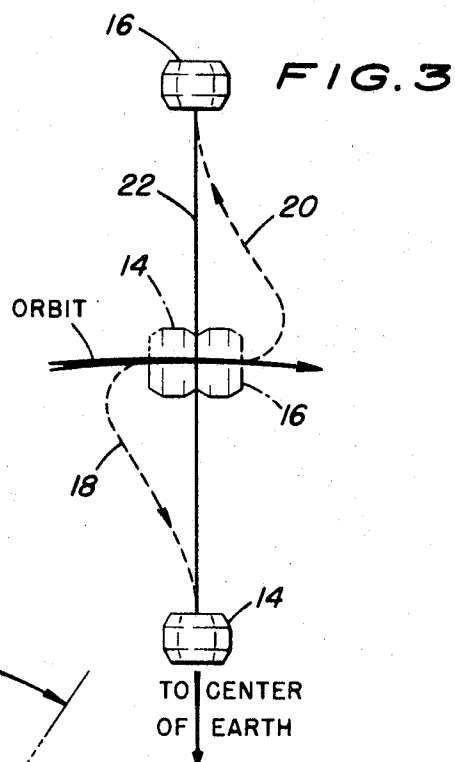
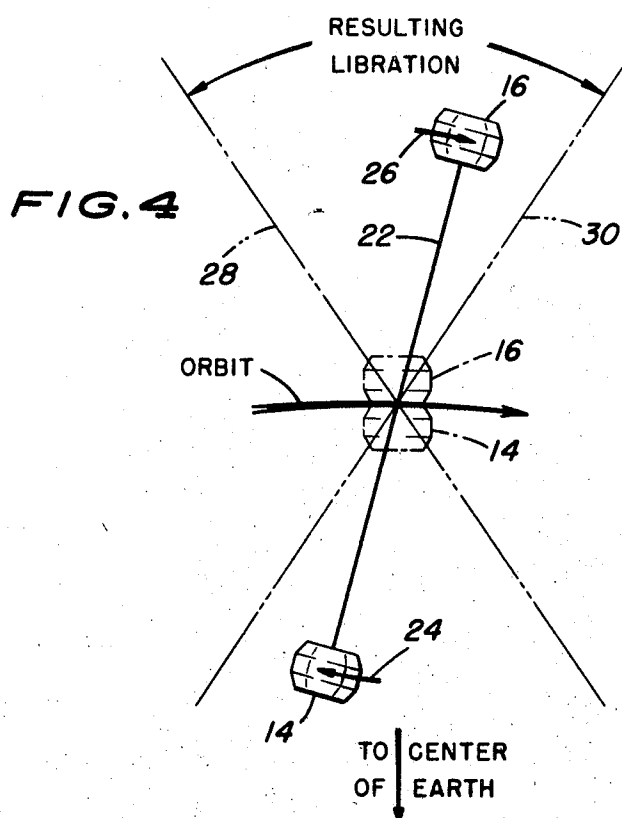
C. J. SWET

3,532,298

METHOD FOR DEPLOYING AND STABILIZING ORBITING STRUCTURES

Filed Oct. 31, 1967

5 Sheets-Sheet 2



CHARLES J. SWET
INVENTOR

Oct. 6, 1970

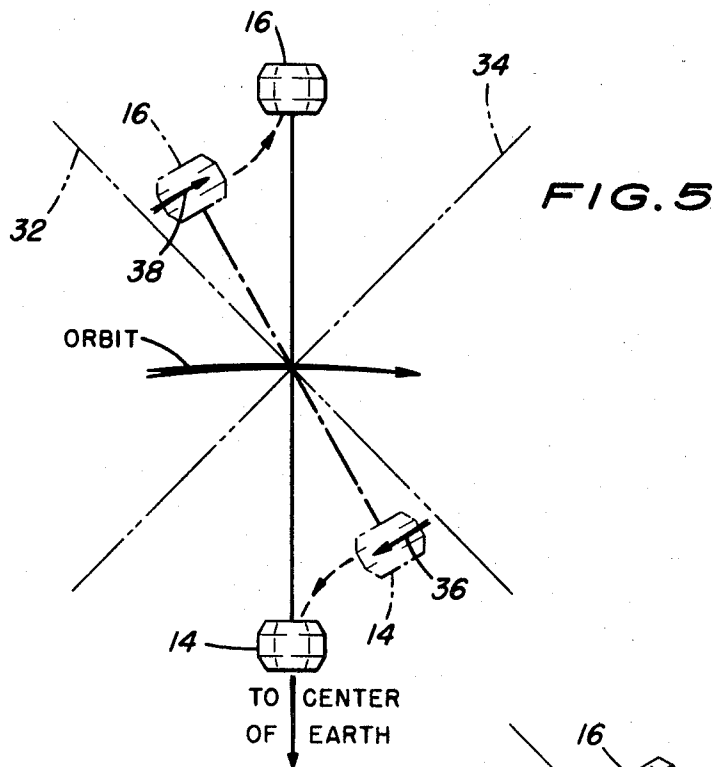
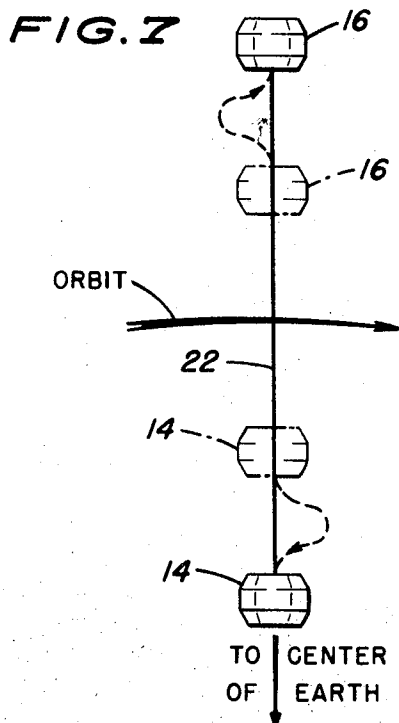
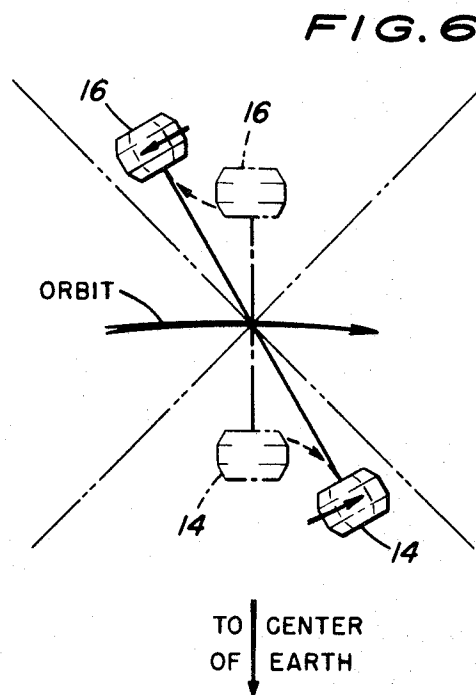
C. J. SWET

3,532,298

METHOD FOR DEPLOYING AND STABILIZING ORBITING STRUCTURES

Filed Oct. 31, 1967

5 Sheets-Sheet 3



CHARLES J. SWET
INVENTOR

Oct. 6, 1970

C. J. SWET

3,532,298

METHOD FOR DEPLOYING AND STABILIZING ORBITING STRUCTURES

Filed Oct. 31, 1967

5 Sheets-Sheet 4

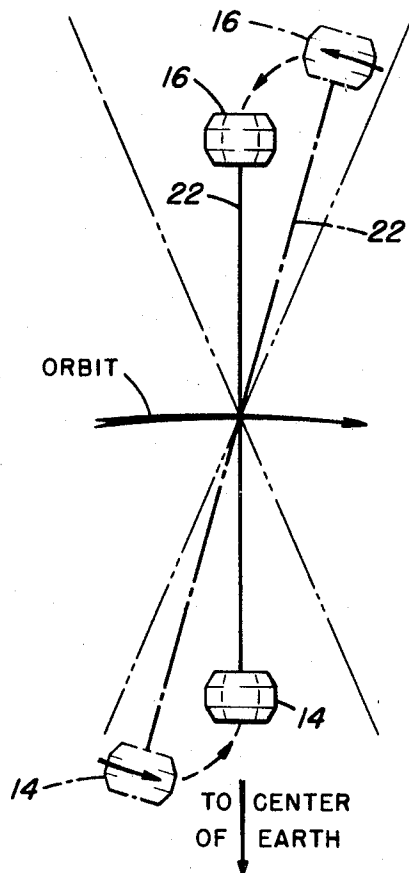


FIG. 8

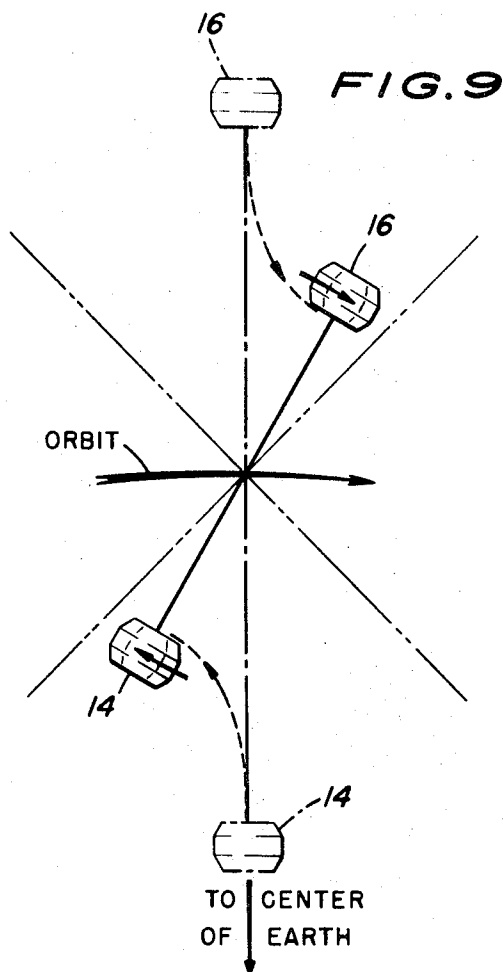


FIG. 9

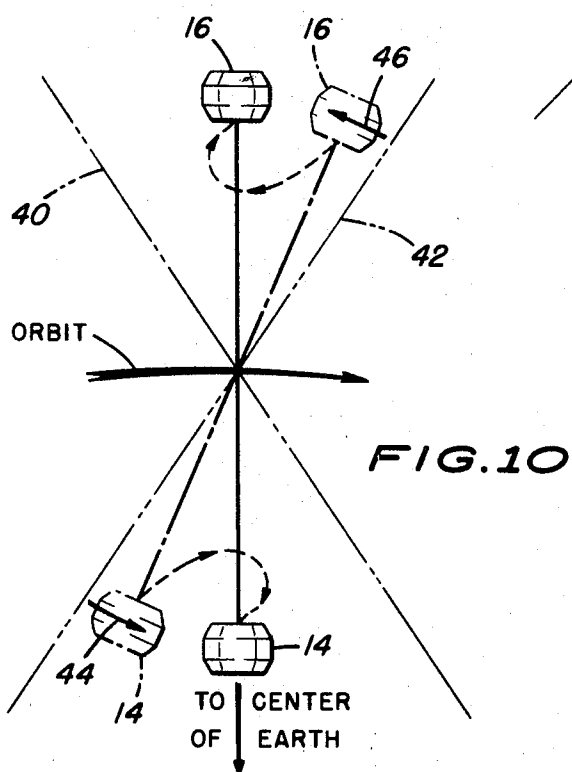


FIG. 10

CHARLES J. SWET
INVENTOR

Oct. 6, 1970

C. J. SWET

3,532,298

METHOD FOR DEPLOYING AND STABILIZING ORBITING STRUCTURES

Filed Oct. 31, 1967

5 Sheets-Sheet 5

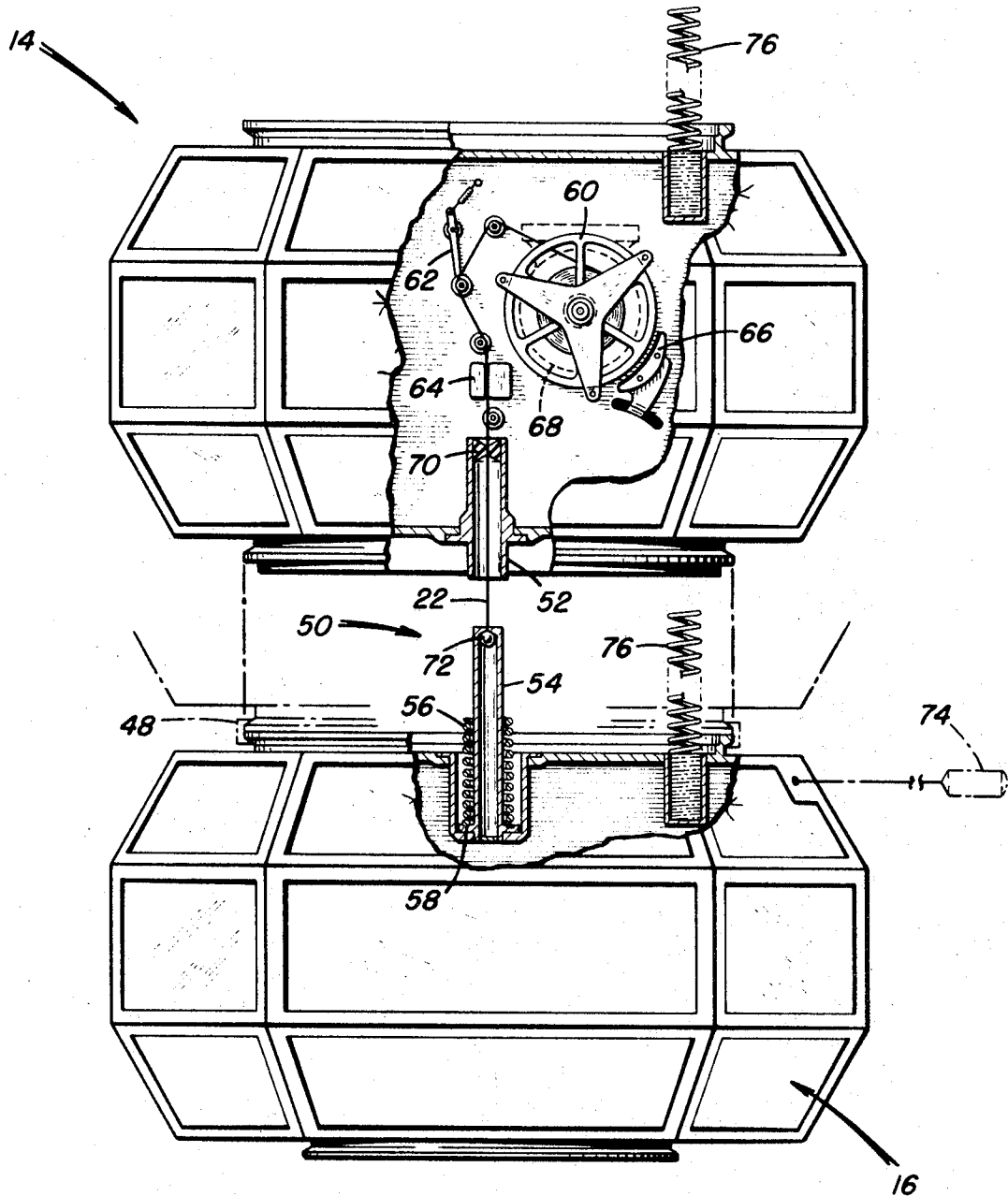


FIG. 11

CHARLES J. SWET
INVENTOR

1

3,532,298

METHOD FOR DEPLOYING AND STABILIZING ORBITING STRUCTURES

Charles J. Swet, Mount Airy, Md., assignor, by mesne assignments, to the United States of America as represented by the Secretary of the Navy

Filed Oct. 31, 1967, Ser. No. 679,404

Int. Cl. B64g 1/00

U.S. Cl. 244—1

16 Claims

ABSTRACT OF THE DISCLOSURE

The subject invention relates to a method for deploying and stabilizing a plurality of orbiting structures which are joined together by flexible tethers. More particularly, the subject invention contemplates the deployment of a plurality of tether-connected orbiting structures into individual orbits, whereby said deployment results in librationless orbital capture.

The instant tether is housed on a spool and is reeled out, preferably under slight tension, so that the individual orbiting structures interact in such a manner that libration is avoided. The reel-out scheme can be of the single-step reel-out variety, the plural-step reel-out variety, or the reel-out-reel-in variety.

BACKGROUND OF THE INVENTION

Field of the invention

The subject invention relates to the field of orbiting satellites. More particularly, the subject invention relates to a method for deploying a plurality of satellites, connected together by ribbon-like tethers, whereby each satellite experiences an individual orbit and whereby deployment is accomplished without the introduction of undesirable libration.

Description of the prior art

The deployment of a plurality of tether-connected orbiting structures is not new. This is evidenced by Pat. No. 3,241,142 issued to Herbert P. Raabe on Mar. 15, 1966. The Raabe patent deals with the gravity stabilization of a tether-connected system comprising a main body in the form of a reflector and an auxiliary body in the form of a capsule; and more particularly, Raabe deals with damping the libration resulting from deploying the main body and the auxiliary body into separate orbits. Reentering, Raabe deals with the removal of the "unavoidable" libration accompanying the deployment of a plurality of tether-connected orbiting bodies.

SUMMARY OF THE INVENTION

The subject invention relates to a method for deploying a plurality of tether-connected bodies into separate and distinct orbits in such a manner that such orbits are attained without causing libration. Therefore, whereas Raabe attempts to damp "unavoidable" libration, the instant invention provides a deployment scheme wherein the "unavoidable" libration is, in fact, avoided.

It is therefore an object of the present invention to provide a method for deploying a plurality of bodies into separate but related orbits.

It is another object of the invention to provide a method for deploying a plurality of tether-connected bodies into separate but related orbits.

It is a further object of the invention to provide a method for deploying a plurality of tether-connected bodies whereby deployment is accomplished without the introduction of libration.

It is still another object of the invention to provide a

2

method for deploying a plurality of tether-connected bodies whereby time consuming libration removing maneuvers are eliminated.

It is yet a further object of the invention to provide a mathematical model from which the ideal magnitudes of the libration-minimizing parameters can be determined.

These and other objects of the invention, and many of the attendant advantages thereof, will become readily apparent from the following description taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic representation of the steps involved in launching and deploying a plurality of tether-connected bodies;

FIG. 2 is a schematic representation of a one-step perfect capture deployment wherein initial separation is radial;

FIG. 3 is a schematic representation of a one-step perfect capture deployment wherein initial separation is tangential;

FIG. 4 is a schematic drawing showing an imperfect capture with resulting libration;

FIG. 5 is a schematic representation of a reel-out libration removing maneuver for correcting the libration resulting from imperfect capture;

FIG. 6 is a schematic representation of a reel-out libration introducing maneuver;

FIG. 7 is a schematic drawing representing a tether-lengthening maneuver which avoids the introduction of libration;

FIG. 8 is a schematic drawing representing a reel-in libration removing maneuver;

FIG. 9 is a schematic drawing showing a reel-in libration causing maneuver;

FIG. 10 is a schematic drawing showing a continuous reel-in reel-out maneuver for removing libration; and

FIG. 11 is a schematic drawing showing a master satellite, a slave satellite and instrumentation useful in practicing the subject deployment method.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

It is often desirable, in the field of earth-orbiting satellites, to provide a plural-satellite system which is gravity stabilized in such a manner that the individual satellites are aligned, at every instant during an orbit, along the local vertical. By using the methods known to the prior art, such a system is attainable, but only by employing a two-step process. In the first step of this process, a plurality of tether-connected satellites are deployed into separate orbits. Since, as is noted above, the prior art knows of no method for deploying tether-connected satellites without the introduction of undesirable libration, the second step is necessarily one of libration removal. Though the methods of the prior art prove useful in providing a gravity stabilized satellite system such as the one disclosed by Raabe, noted above, one major disadvantage exists. This disadvantage resides in the libration removing step. The amount of time necessary to damp the libration inherent in the prior art deployment schemes is directly proportional to the magnitude of the inherent libration; and since the resultant libration is often quite large, the process of libration removal often entails a period sometimes of the order of weeks. It is this time consuming libration removing step that the subject invention seeks to eliminate.

With reference to FIG. 1, there is given a general description of the steps involved in attaining a gravity stabilized multi-satellite system, commencing with the launch and concluding with the final orbital capture. Powered from the earth 10, is a spacecraft shown generally at 12

and comprising a master satellite 14, a slave satellite 16 and a launch vehicle 18. During its orbital injection stage, the spacecraft is spin oriented in the usual manner, and remains spin oriented during the final stage separation, through the elliptical transfer orbit, the firing of the kick-motor and the ejection of the kick-motor. It should be noted that the apogee kick is required only to attain very high altitude orbits such as synchronous orbits. After the satellite reaches a circular orbit, and when the master satellite-slave satellite combination is in alignment with the local vertical, the satellite is despun and the master satellite is caused to separate from the slave satellite. These steps are shown generally at 20. During the separation of the master and slave satellites, the tether is allowed to reel out, preferably under a controlled tension, until again, the master satellite and the slave satellite are in alignment with the local vertical. When this second alignment occurs, tether payout is halted. As is hereinafter explained, the reel-out parameters are calculated so that the desired tether length is reached when the master satellite and the slave satellite are in alignment with the local vertical; and therefore, the master satellite and the slave satellite continue in circular orbits and remain in geocentric alignment with the local vertical.

With reference now to FIGS. 2 and 3, there are shown ideal orbital capture maneuvers involving the two basic modes of initial deployment available for use in the deployment step shown at 20 in FIG. 1. In FIG. 2 there is shown a deployment maneuver involving initial separation of the radial variety; and in FIG. 3 there is shown a deployment maneuver involving initial separation of the tangential variety. These basic separation modes obtain their names from the fact that the initial direction of separation is either radial or tangential with respect to the local vertical. The initial positions of the master and slave satellites are shown in phantom, and the final positions are shown in solid lines. When the master satellite 14 and the slave satellite 16 are caused to separate, they travel along the paths represented by dotted lines 18 and 20, respectively, and ideally, attain separate orbits without libration. When ideal orbital capture is attained, the master satellite 14 and the slave satellite 16 enjoy separate orbits, each satellite being influenced by the other only through the constant pull transmitted to it through a tether 22—said constant pull being the result of the gravity gradient associated with the system and the centrifugal force caused by a fixed tumble rate in the system. It should here be mentioned that the radial separation and the tangential separation are illustrated only to show the two basic modes of separation; and that initial separation falling anywhere between the radial mode and the tangential mode, for the purposes of the instant invention, can also be employed.

Before moving to the imperfect orbital capture and the means for correcting the associated imperfections, it should be noted that when it is desired that the master satellite be facing the earth at all times during an orbit, it is necessary that the tether-connected satellite system tumble once per orbit around its center of mass. Since, under ideal conditions, the tether-connected satellite system tumbles once per orbit, the system has associated therewith a moment of inertia, an angular momentum and an angular rate of tumble. Furthermore, since the subject system is a conservative system, the angular momentum is constant. Therefore, any increase in the moment of inertia causes a decrease in the angular rate of tumble; and any decrease in the moment of inertia causes a corresponding increase in the angular rate of tumble. It is this relationship between the moment of inertia and the angular rate which makes possible the librationless orbital capture attainable by using the teachings of the present invention.

Referring now to FIG. 4, there is shown a deployment scheme which results in an imperfect orbital capture wherein the satellite system librates. As in FIGS. 2 and 3, the initial positions of the satellites are shown in phantom, and the final orbital capture position is shown in solid

lines. Unlike the perfect captures represented in FIGS. 2 and 3, the capture of FIG. 4 is imperfect and the satellite system librates about its center of mass. The instantaneous directions of libration of the master satellite 14 and the slave satellite 16 are shown by arrows 24 and 26, respectively; and the outer limits of the libration are represented by broken lines 28 and 30. Since the system is designed to tumble once per orbit, and since the system further experiences libration, it is obvious that during an orbit the system will tumble at rates greater than and less than 1 r.p.o. depending upon the instantaneous direction of libration. For instance, since it is desired that the satellite system tumble at 1 r.p.o. in a clockwise direction (viewing FIG. 4) and since the instantaneous direction of libration is clockwise, it is obvious that the satellite system tumbles at a rate of greater than 1 r.p.o. Hereinafter, the direction of libration shown in FIG. 4 will be termed the orbital direction; and the direction of libration opposite that shown in FIG. 4 will be termed the counter-orbital direction. Therefore, when the satellite system librates in the counter-orbital direction, the system tumbles at a rate of less than 1 r.p.o.; and when the satellite system librates in the orbital direction the system tumbles at a rate greater than 1 r.p.o.

It follows from the above discussion that a constant tumble rate of 1 r.p.o. is equivalent to a librationless orbital capture. It is the purpose of the instant invention to provide a method for attaining a constant tumble rate of 1 r.p.o. It also follows from the above discussion that the rate of tumble can be altered by causing a corresponding alteration in the moment of inertia. It is therefore a more particular purpose of the invention to attain a constant tumble rate of 1 r.p.o. by adjusting the moment of inertia of the tethered system in such a manner that the proportional relationship between the moment of inertia, the angular momentum and the angular rate of tumble is such that the angular rate equals 1 r.p.o.

With reference now to FIG. 5, a deployment maneuver which makes use of the balance between the moment of inertia and the angular rate of tumble will be explained. The master satellite 14 and the slave satellite 16 are separated in the manner described with reference to FIG. 2 or FIG. 3; but the ideal orbital capture is not attained. Instead, an orbital capture similar to that shown in FIG. 4 is attained. Therefore, the master satellite 14 and the slave satellite 16 librate between the limits shown by dotted lines 32 and 34. The librating satellites are shown in phantom; and the instantaneous directions of libration are shown by arrows 36 and 38. When the satellites are in the positions and move in the directions as indicated in FIG. 5, the tumble rate is greater than the desired rate of 1 r.p.o. It follows that an increase in the moment of inertia tends to correct the too-rapid tumble rate since an increase in the moment of inertia causes a decrease in the angular rate of tumble in the conservative system. Therefore, if the tether is allowed to further pay-out while the satellite system librates in the orbital direction, the moment of inertia of the system increases and therefore the angular rate of tumble of said system decreases. If, then, it is possible to calculate the moment of inertia necessary to bring the angular rate of tumble to 1 r.p.o., it is possible to deploy a plurality of tether connected satellites in such a manner that the final orbital capture can be attained without the attendance of libration. Such a calculation is easily made by one skilled in art.

Before moving to a discussion of the remaining figures, it should be mentioned that the subject invention can be practiced under two basic sets of requirements. First, the subject deployment scheme is useful when the project requires only a librationless orbital capture; and second, the subject deployment scheme is useful when the project requires both a librationless orbital capture and a predetermined and fixed final tether length. Under the first basic set of requirements, no problems exist. The satellites are deployed and any accompanying libration is re-

moved by the maneuver described above with reference to FIG. 5. Under the second basic set of requirements, though, one is limited by the desired tether length. Therefore, if the FIG. 5 maneuver is to be useful, initial deployment (shown in phantom) must be such that the tether length is less than the predetermined and desired final tether length. What then must be done to attain a librationless capture having a predetermined tether length if the initial (short-tether) deployment is librationless?

With reference to FIG. 6, there is explained a method for increasing the tether length, in a two-step process, so that a librationless system having a too-short tether is transformed into a librationless system having a tether of the required final length. The master satellite 14 and the slave satellite 16 are shown in phantom as they would appear should a librationless deployment occur. Though a librationless deployment results, it is noted that the tether length is not of the desired final tether length. Therefore, a correction must be made. As noted above, a relationship exists between the moment of inertia, the angular momentum and the angular rate of tumble associated with the satellite system. This relationship dictates that the angular rate can be changed by altering the moment of inertia. Therefore, as is shown in FIG. 6, the tether is allowed to pay-out to an extent greater than the initial pay-out length but less than the desired final tether length. This increase in the tether length causes an increase in the moment of inertia, and therefore, the angular rate of tumble associated with the satellite system decreases. Rather than only decreasing the angular rate of tumble, the increase in tether length causes libration to be set up in the satellite system. Once this libration occurs, the libration removing process shown in FIG. 5 becomes appropriate for attaining the desired tether length in such a manner that a librationless system results.

Referring now to FIG. 7, there is shown, in phantom, a master satellite 14 and a slave satellite 16 as they appeared, also in phantom, in FIG. 6. While FIG. 6 shows the first step of a two-step libration removing process, it is thought possible to move, in one step, from a librationless system having a too-short tether length to a librationless system having tether length equal to the required final tether length. Therefore, it is shown in FIG. 7 that at some instant during the orbit the tether is allowed to pay-out, under a predetermined schedule of tether tension, so that when the desired tether length is reached, pay-out is snubbed; and the resultant system is a librationless one in which the tether length is equal to the desired tether length.

As noted above, one alternative which presents itself is that of initially deploying the satellite bodies in such a manner that the length of the tether is less than the desired final length. Another alternative which presents itself is to deploy the bodies in such a manner that the initial tether length is greater than the desired final tether length. This second alternative is illustrated in FIG. 8. The master satellite 14 and the slave satellite 16 are allowed to separate until the tether length is greater than the desired tether length set by the requirements of the project. FIG. 8 shows the situation when libration results when such a deployment is practiced. Similar to the maneuver used in FIG. 5 for removing libration, FIG. 8 shows a maneuver which can be considered the converse of that shown in FIG. 5. More particularly, FIG. 8 shows that when the satellite bodies librate in the counter orbital direction, that is, when they tumble at a rate of less than 1 r.p.o., a tether reel-in maneuver is performed, the result of which is a librationless satellite system wherein the tether length is equal to the desired final tether length. That this is, in fact, possible is obvious when one notes that the process shown diagrammatically in FIG. 8 is one wherein the moment of inertia of the satellite system is decreased an amount which causes an increase in the rate of tumble so that the final tumble rate is equal to 1 r.p.o.

As is the case in FIG. 6, it is always possible that a librationless deployment will result even though the tether length is other than the desired final tether length. When this occurs, a two-step maneuver can be performed which first introduces libration and then removes libration. Referring then to FIG. 9, there is shown, in phantom, the master satellite 14 and the slave satellite 16 as they appear when a librationless orbital capture results from a deployment wherein the tether length is greater than the desired final tether length. At any time during the orbit, a reel-in maneuver is performed and libration is introduced due to the inter-relationship between the moment of inertia and the angular rate of tumble. The amount that the tether is shortened in the libration-causing step is again left to the discretion of the practitioner. The practitioner can shorten the tether an amount which results in a tether length greater than the desired tether length but less than the initial tether length; or the practitioner can shorten the tether an amount which results in a tether length less than the desired final tether length. When the tether is shortened only an amount which results in a tether length greater than the desired tether length, the libration removing step shown in FIG. 8 is used to attain the desired final tether length; and when the tether is shortened an amount which results in a tether length less than the desired tether length, the libration removing step shown in FIG. 5 is used to attain the desired tether length.

In the discussion referenced to FIGS. 5 through 9, it has been assumed that the initial tether length is calculated to be either less than or greater than the desired final tether length. It is not thought that such a length difference is necessary. In particular, the master satellite and the slave satellite can be deployed in such a manner that the desired tether length is immediately reached. If such a length is attained without the introduction of libration, the deployment is complete. If such a length is attained with the introduction of libration however, a correction must be made. Referring then to FIG. 10, the master satellite 14 and the slave satellite 16 are shown to be librating (in phantom) between the dotted lines 40 and 42. It follows from the discussion given above that if the tether length is shortened, the angular rate of tumble increases since the moment of inertia decreases. And similarly, if the tether length increases, the angular rate of tumble decreases since the moment of inertia increases. Therefore, when the master satellite 14 and the slave satellite 16 occupy the positions and are traveling in the directions shown by arrows 44 and 46, respectively, it is necessary to increase the angular rate of tumble, and therefore it is necessary to decrease the tether length. But if the tether length is decreased, the separation between the master satellite 14 and the slave satellite 16 is less than the desired separation dictated by the project. Therefore, in order to attain the desired separation, the tether must then be increased in length. With continuing reference to FIG. 10, there is shown a continuous process of first shortening the tether and then lengthening the tether, this continuing process removing the libration in a satellite system without changing the overall distance between the individual satellites in such a system.

Summarizing what heretofore has been explained, FIG. 1 is a schematic representation of the general objective of the instant invention, namely, to deploy a plurality of tether-connected orbiting satellites into separate orbits in such a manner that libration is avoided. FIGS. 2 and 3 illustrate the two basic modes of initial separation, namely, the radial mode and the tangential mode, respectively. FIG. 4 is a less optimistic but a more realistic view of the probable results (libration) of a deployment maneuver using the calculated ideal values for the initial separation velocity, the tether tension and the final tether length. FIGS. 5 through 7 are illustrative of the concept of deploying a plurality of tether-connected satel-

lites in such a manner that the tether reel-out maneuver is halted before the desired tether length is attained, and is further illustrative of the concept of attaining the desired tether length without the introduction of libration. FIGS. 8 and 9 are illustrative of the concept of deploying a plurality of tether-connected satellites in such a manner that the tether reel-out maneuver is not halted until the tether length is greater than the desired tether length, and is further illustrative of the concept of attaining the desired tether length without the introduction of libration. And finally, FIG. 10 is a schematic drawing showing the possibility of deploying a plurality of tether-connected satellites in such a manner that the tether reel-out maneuver is halted precisely when the tether length is equal to the desired final tether length, and is further illustrative of the concept of removing any resulting libration without altering the overall tether length.

It is known that an ideal one-step deployment can be attained if the proper values of initial separation velocity and final tether length, as well as a proper schedule of tether tension, can be determined; but there are no known equations or mathematical models into which a query can be injected and out of which can be extracted an answer representing the exact tether tension, separation velocity and tether length for a perfect librationless deployment. This does not, though, close the door on the successful application of the instant invention. Sets of equations can be written which give the inter-relationship between the three variables of interest, namely, the initial separation velocity, the tether tension and the tether length, and, at the same time, give the inter-relationship between the well-known Keplers associated with every body in orbit. Once these equations are written, representative values of the three variables can be injected therein and, with the aid of a computer, the Keplers can be examined at fixed intervals during the orbit. Since the Keplers define the orbit, they also define whether an orbiting body is experiencing libration. If it is found that the magnitudes of the three variables injected into the set of equations are not proper (that is, do not correspond to a librationless orbital capture), the variables are incrementally amended and the equations are re-examined. In this manner, the set of equations is capable of indicating values of separation velocity, tension and length which, ideally, correspond to a perfect orbital capture. The following Equations 1 through 5 make up a non-exclusive set of equations which can be used to determine the proper inter-relationship between the tether tension, the initial separation velocity between the master and slave satellites and the final tether length so that a librationless orbital capture will ideally result.

Change to semi-major axis:

$$da = \frac{2a^2 v_\eta}{K} dv_\eta - \frac{2a^2 e}{C} \sin(\eta_e - \eta_p) dv_p + (0) dv_{op} \quad (1)$$

Change to eccentricity:

$$de = \frac{C}{\rho_e e a K} [b^2 - \rho_e^2] dv_\eta - \frac{C}{K} \sin(\eta_e - \eta_p) dv_p + (0) dv_{op} \quad (2)$$

Change to argument of perigee:

$$d\eta_p = \frac{1}{C e} \left(\frac{C^2}{K} + \rho_e \right) \sin(\eta_e - \eta_p) dv_\eta + \frac{C}{e K} \cos(\eta_e - \eta_p) dv_p \dots - \frac{1}{v_\eta} \frac{\sin(\eta - \eta_\Omega)}{\tan i} dv_{op} \quad (3)$$

Change to inclination:

$$di = (0) dv_\eta + (0) dv_p + \frac{1}{v_\eta} \cos \eta_e - \eta_\Omega dv_{op} \quad (4)$$

and change to ascending node:

$$d\Omega = (0) dv_\eta + (0) dv_p + \frac{1}{v_\eta} \frac{\sin(\eta_e - \eta_\Omega)}{\sin i} dv_{op} \quad (5)$$

wherein:

- A_η = Azimuthal acceleration
- A_p = Radial acceleration ($A_p \perp A_\eta$)
- g = Acceleration due to gravity
- K = GM = Gravitational constant times earth mass
- ρ = Radius vector from earth center to orbiting body
- η = True anomaly measured from peri-apsis
- a = Semi-major axis of ellipse
- b = Semi-minor axis of ellipse
- e = Eccentricity
- Ω = Longitude of ascending node
- i = Inclination
- v_p = Radial velocity
- v_η = Azimuthal velocity ($v_p \perp v_\eta$)
- dv_p = Radial velocity increment
- dv_η = Azimuthal velocity increment
- dv_{op} = Velocity increment normal to initial orbital plane
- t = Time

Subscripts:

- e = Epoch
- p = Parameter taken at perigee and
- a = Parameter taken at apogee.

In using the set of equations given above, the desired tether length was chosen to be of the order of three nautical miles and the initial separation velocity and the tether tension were incrementally varied, one set of values being used per computer run. (Although tether tension does not appear explicitly in these equations, its selected magnitude and direction—always in the line joining the two bodies—determines the velocity increments do_p , dv_η and dv_{op} ; i.e., it is the perturbation that causes each body to deviate from an otherwise independent orbit.) The computer was programmed to "look" at the position of the master and slave satellites, in terms of the associated Keplers, at fixed intervals of 300 seconds. The computer results, which gave the position of the individual satellites every 300 seconds, were plotted graphically. Then one of the two parameters was varied and a further computer run was taken. It becomes obvious that the magnitudes of the tether tension and the initial separating velocity which correspond to a perfect orbital capture can be determined after relatively few runs of the computer.

As is noted above, the above set of equations based on the Keplers are not exclusive and are therefore not intended to limit the instant invention in any manner. It should further be noted that the instant set of equations does not take into account such variables as tether flexibility, radiation pressure, and so forth; but it should be obvious that equations can be written by those skilled in the art to take into account such variables.

With reference now to FIG. 11, there follows a description of one physical configuration of a stellite system which makes possible the practice of the instant invention. The master satellite is shown at 14 and the slave satellite is shown at 16. These satellites are connected together by a frangible seal 48 which can take the form of any seal well-known in the art. Effecting the alignment of the master satellite 14 with respect to the slave satellite 16 is a separation guide shown generally at 50. Said separation guide 50 comprises a female member 52 attached to the master satellite and a male member 54 attached to the slave satellite, said male member 54 being slidably fitted within said female member 52.

When the seal 48 is caused to rupture, the master satellite 14 and the slave satellite 16 are caused to separate by the action of a spring 56 which encircles the male member 54 and is attached to the body of the slave satellite 16 at 58. Controlling the manner in which the master satellite and the slave satellite separate, and causing the master satellite and the slave satellite to function as parts

of a single unit, is a tether system. The greater portion of this tether system is housed within the master satellite and comprises a reel 60 onto which is wound a tether 22, a tension sensor 62 for noting the instantaneous tension in the tether 22 and a photo sensor 64 for noting the length of the tether 22 which lies outside the master satellite. Providing the tether system with the capability of reeling-out and reeling-in the tether by following a predetermined schedule of tension, is a brake 66 and a motor 68, both said brake and said motor controlling the reel 60 in its clockwise and its counterclockwise directions of rotation. After the tether 22 leaves the reel 60 and is threaded through the tension sensor 62 and the photo sensor 64, said tether passes between a pair of guides 70 which are fixedly housed within the female member 52 of the separation guide 50, and is then fixedly attached to the male member 54 of the separation guide 50 at 72.

The satellites shown in FIG. 11 further include Yo-yo despin weights 74 (only one being shown) for accomplishing the despin maneuver shown in FIG. 1 at 20, and self-extending helical antennas 76 which form a part of the telemetry system associated with the satellite system.

In conclusion, there has been disclosed a method for deploying a plurality of tether-connected satellites into separate orbits without the introduction of undesirable libration. There has further been disclosed means for accomplishing the above-noted depolyment method. And finally, there has been disclosed a mathematical model for aiding the practitioner in determining the magnitudes of the physical parameters most apt to result in a perfect, or librationless, orbital capture.

It should again be mentioned that the subject invention can be practiced by using other means and other mathematical models than are disclosed herein. It should further be mentioned that while the above disclosure has been concerned with a two-satellite system, the instant invention is equally applicable to satellite systems comprising unlimited numbers of individual satellites. Therefore, it is intended that the scope of the instant invention not be limited by the description given hereinabove.

I claim:

1. A method for deploying an orbiting satellite system in the form of a plurality of tether-connected satellites, whereby said plurality of satellites are placed in aligned orbits and whereby said satellite system is caused to tumble at a predetermined rate, comprising the steps of:

- placing into orbit, as a single unit, a plurality of satellites;
- applying a force tending to cause said plurality of satellites to move into separate orbits;
- allowing said plurality of satellites to move into separate orbits by permitting the length of a connecting tether to gradually increase; and
- lengthening the connecting tether in such a manner that the relationship between the moment of inertia, the angular momentum, and the angular rate of tumble associated with said satellite system is such that the angular rate is equal to said predetermined tumble rate.

2. The method of claim 1 wherein the length of the connecting tether is allowed to increase under a predetermined schedule of tension.

3. The method of claim 2 wherein said satellite separating force is applied at a time when the plurality of satellites forming said single unit is in alignment with the local vertical.

4. The method of claim 3 wherein said tether is wound on a reel and wherein said reel is provided with means for controlling rotation of the reel.

5. A method for deploying an orbiting satellite system in the form of a plurality of tether-connected satellites, whereby said plurality of satellites are placed into aligned orbits and whereby said satellite system is caused to tumble at a predetermined rate, comprising the steps of

placing into orbit, as a single unit, a plurality of satellites,

applying a force tending to cause said plurality of satellites to move into separate orbits;

allowing said plurality of satellites to move into separate orbits by permitting the length of a connecting tether to gradually increase; and

shortening the connecting tether in such a manner that the relationship between the moment of inertia, the angular momentum, and the angular rate of tumble associated with said satellite system is such that the angular rate is equal to said predetermined tumble rate.

6. The method of claim 5 wherein the length of the connecting tether is allowed to decrease under a predetermined schedule of tension.

7. The method of claim 6 wherein said satellite separating force is applied at a time when the plurality of satellites forming said single unit is in alignment with the local vertical.

8. The method of claim 7 wherein said tether is wound on a reel and wherein said reel is provided with means for controlling its rotation.

9. A method for deploying an orbiting satellite system in the form of a plurality of tether-connected satellites, whereby one of said plurality of satellites always faces the body around which said system is orbiting and whereby said plurality of satellites is always in alignment with the local vertical, comprising the steps of

placing into orbit, as a single unit, a plurality of satellites;

applying a force tending to cause said plurality of satellites to move into separate orbits;

allowing said plurality of satellites to move into separate orbits by permitting the length of a connecting tether to gradually increase,

whereby the gradual increase in the tether length is controlled by a predetermined schedule of tether tension; and

lengthening the connecting tether in such a manner that the relationship between the moment of inertia, the angular momentum, and the angular rate of tumble associated with said satellite system is such that the angular rate is equal to one revolution per orbit.

10. The method of claim 9 wherein the satellite separating force is applied at a time when the plurality of satellites forming said single unit are in alignment with the local vertical.

11. The method of claim 9 wherein said lengthening of the connecting tether terminates at a time when said plurality of tether-connected satellites are in alignment with the local vertical.

12. The method of claim 9 wherein said tether is wound on a reel and wherein said reel is provided with means for controlling its rotation.

13. A method for deploying an orbiting satellite system in the form of a plurality of tether-connected satellites, whereby one of said plurality of satellites always faces the body around which said system is orbiting and whereby said plurality of satellites are always in alignment with the local vertical, comprising the steps of

placing into orbit, as a single unit, a plurality of satellites;

applying a force tending to cause said plurality of satellites to move into separate orbits;

allowing said plurality of satellites to move into separate orbits by permitting the length of a connecting tether to gradually increase,

whereby the gradual increase in the tether length is controlled by a predetermined schedule of tether tension; and

shortening the connecting tether in such a manner that the relationship between the moment of inertia, the angular momentum, and the angular rate of tumble

11

associated with said satellite system is such that the angular rate is equal to one revolution per orbit.

14. The method of claim 13 wherein the satellite separating force is applied at a time when the plurality of satellites forming said single unit are in alignment with the local vertical.

15. The method of claim 13 wherein said shortening of the connecting tether terminates at a time when said plurality of tether-connected satellites are in alignment with the local vertical.

16. The method of claim 13 wherein said tether is wound on a reel and wherein said reel is provided with means for controlling its rotation.

12

References Cited

UNITED STATES PATENTS

3,206,142	9/1965	Raabe.
3,241,142	3/1966	Raabe.
3,333,798	8/1967	Dryden.

OTHER REFERENCES

R. B. Hershner: Gravity-gradient Stabilization of Satellites; Astronautics and Aerospace Engineering; September 1963, pp. 18-22.

MILTON BUCHLER, Primary Examiner

JEFFREY L. FORMAN, Assistant Examiner