

(43) International Publication Date
11 August 2016 (11.08.2016)

(51) International Patent Classification:

B64G 1/24 (2006.01) B64G 1/40 (2006.01)
B64G 1/26 (2006.01)

(21) International Application Number:

PCT/IL2016/050104

(22) International Filing Date:

1 February 2016 (01.02.2016)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

237081 4 February 2015 (04.02.2015) IL

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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM,

DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— of inventorship (Rule 4.17(iv))

Published:

— with international search report (Art. 21(3))

— before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))

(54) Title: METHOD AND SYSTEM FOR STATION KEEPING OF GEO SATELLITES

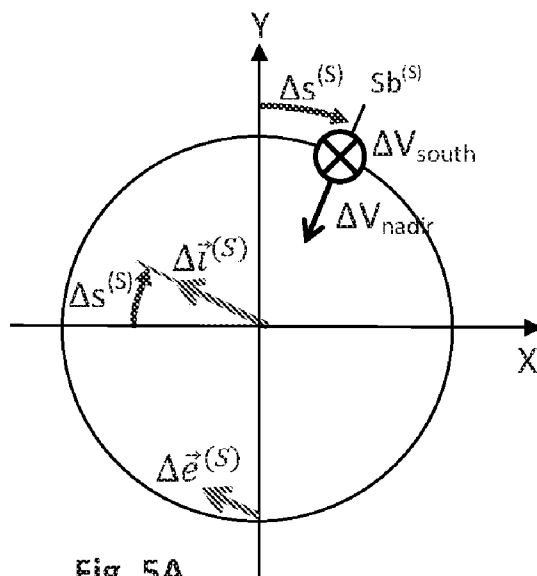


Fig. 5A

(57) Abstract: A method for maneuvering a satellite is provided and a system employing it is disclosed. The maneuvering includes performing two or more complementary north and south maneuvers to adjust an inclination of an orbit of a satellite by desired inclination correction Δi . The complementary north and south maneuvers are performed by operating north and south thrusters of the satellite, which are respectively installed at panels of the satellite with respective cant angles from the north-south axis so as to produce significant radial component, to generate respective thrust delta-Vs for respectively accelerating the satellite by two or more predetermined supplemental velocities at two or more corresponding sideral angles along the orbit. The maneuvering is characterized by shifting at least one of the sideral angles of the two or more complementary maneuvers, to increase or decrease it, with respect to the optimal sideral angle, which is perpendicular to the desired overall inclination correction Δi , and thereby adjusting the inclination i of the orbit by the desired inclination correction Δi while also adjusting an eccentricity e of the orbit by a desired eccentricity correction Δe .

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METHOD AND SYSTEM FOR STATION KEEPING OF GEO SATELLITES

TECHNOLOGICAL FIELD

The invention is in the field of geostationary satellites' station keeping maneuvers, and particularly relates to maneuvers performed by south and north electrical thrusters of a satellite.

5 BACKGROUND

Various types of satellites, such as communication satellites and broadcast satellites, are *geostationary satellites* operating in geostationary orbits. A geostationary orbit is generically achieved at a nearly constant altitude of about 35,786km above the Equator, which in turn corresponds to an orbital velocity of about 3.07km/s resulting in
10 an *orbital period* of one *sidereal day*. In the sidereal time scale, which is based on the Earth's rate of rotation measured relative to a fixed stars system, a *sidereal day* is the time it takes the Earth to make one rotation relative to the vernal equinox (which takes about 1,436 minutes). This ensures that the *geostationary* satellite is locked to the Earth's rotational period and has a stationary footprint (or sub-orbital point) on the
15 ground. The term *footprint* refers to the ground area of coverage of the satellite (e.g. of the equipment installed thereon).

The geostationary orbit is subject to orbital perturbations caused by anomalies in the gravitational field of the Earth, the gravitational effects of the sun and moon, and solar radiation pressure. A combination of lunar gravity, solar gravity, and the flattening
20 of the Earth at its poles, causes an *orbital plane precession perturbation*, changing the inclination of the orbit. More specifically, the *orbital plane precession perturbation* causes a precession motion of the orbital plane of any geostationary object within a period of about 53 years, and an initial inclination gradient of about 0.85 degrees per year, achieving a maximum inclination of 15 degrees after 26.5 years.

25 In order to correct the orbit and compensate for the *orbital plane precession perturbation*, regular *station-keeping*/orbital-maneuvers are performed by the north

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and/or the south thrusters of the satellite. The total changes in the satellite velocity (the total delta-V) affected by such maneuvers amount to approximately 50m/s per year.

Another type of orbit perturbation relates to in-plane orbit perturbations, which include the longitude drift perturbation and the eccentricity perturbation. A longitude drift perturbation is generally caused by the asymmetry of the Earth (e.g. due to the earth's equator being slightly elliptical). There are two stable longitudinal equilibrium points (at 75.3E, and at 104.7W) and two unstable longitudinal equilibrium points (at 165.3E, and at 14.7W), and any geostationary object/satellite placed between them would be drifted/accelerated towards the stable equilibrium position, causing a periodic longitude variation/wobbling. The correction of longitude drift perturbation effect requires orbit control maneuvers with a delta-V of up to about 2m/s per year, depending on the longitude of the satellite. The orbit's eccentricity is influenced by eccentricity perturbation caused mainly by solar radiation pressure which exerts relatively small forces on the satellite affecting the development of orbit eccentricity. This results in daily librations of the longitude of the sub-orbital point of the satellite's orbit.

The station keeping task of a geostationary orbit includes adequate inclination control, which assures that the latitude of the satellite's sub-orbital point remains properly bounded, complying with the operators' requirements/station keeping policy of the satellite. Currently it is common to require that the inclination be smaller than 0.05°. In case of co-location, i.e. of more than one satellite sharing the same longitudinal slot, the maximum inclination requirement can be even more stringent. Additionally, station keeping of a geostationary satellite includes coping with the longitudinal drift and controlling the orbit's eccentricity to maintain the longitude of the sub-orbital point (e.g. the daily librations of the longitude) within the desired range, which is typically [-0.05°, +0.05°] about the nominal longitude.

Controlling the inclination of a satellite is generally performed by operating thrusters installed on the north and/or south panels of the satellite at predetermined locations (times) along the orbit to provide the predetermined appropriate delta-V's. In general, thrusters installed on the east and west panels, (perpendicular to them) are for adjusting both longitude and eccentricity.

For example U.S. patent No. 5,124,925 discloses a method for east/west station keeping of a geostationary satellite that maintains the osculating value of longitude from exceeding a specified deadband for a specified drift period between maneuvers. In the

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planning, the mean longitude, the mean drift rate and the mean eccentricity vector are calculated and then maneuvers are executed to maintain the values below a magnitude, such that the osculating longitude will be within the specified deadband over a specified longitude drift period. The target conditions are achieved through a plurality of
5 maneuvers which initiate a period of free drift which lasts for a specified number of days. During the free-drift period, longitude remains within its deadband, and no additional maneuvers are needed or are performed. The method has the advantage that it can take into account limitations on thruster on-time by allowing for a generalized number of station keeping maneuvers.

10 U.S. publication No. 2002/036250 discloses a method for maintaining the orbital position of a geostationary satellite by compensating the perturbational effects of interfering influences. The range of the satellite orbit is determined, relative to a space-fixed reference system. Position maintaining actuators of the satellite are activated within the determined range.

15 **GENERAL DESCRIPTION**

The need for station keeping/orbit control maneuvers places a major limitation on the lifetime of a satellite. In the absence of renewable propulsion techniques for implementing the orbit control maneuvers, such maneuvers are performed with the
20 consumption of a thruster propellant, the amount of which is limited in the satellite tanks.

In conventional techniques, north/south thrusters are activated controlling the inclination, and the east/west thrusters' activation provides control of the in-plane parameters of longitude and eccentricity.

25 The total thrust delta-V (ΔV), required in the control of the inclination is much larger than that required to maintain the in-plane parameters (such as longitudinal drift and orbit eccentricity), and constitutes the main parameter influencing the mission's lifetime. The thrust delta-V required for longitude control is only a few percent of that required for inclination control. Eccentricity control is not needed in some missions, but
30 in others it may require a few additional percent of the thrust delta-V required for inclination control.

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The term delta-V (also referred to herein as thrust delta-V or denoted ΔV), is used herein to designate an astro-dynamic change in velocity needed for making an orbital maneuver, i.e. to change from one trajectory to another.

The thrusters specifically considered in the following are the north and the south
5 thrusters which are in general used for inclination correction maneuvers. The north and south thrusters are installed respectively on the north and the south panels/sides/walls of the satellite, with or without deviation angles from the north-south direction, also called cant angles, and are intended to provide thrust mainly in the south and north directions respectively. Other thrusters that are typically installed on a satellite include east and
10 west thrusters, which are installed respectively on the east and west panels/sides/walls of the satellite, providing thrust delta-Vs mainly in the west and east directions respectively.

In this regards, it is noted that in certain types of satellites, such as GEO satellites, one or more of the body axes of the satellite are maintained with
15 approximately fixed orientation relative to a reference coordinate system external to the satellite when it is in orbit (e.g. the Orbit Coordinate System). Accordingly, the body axes of the satellite are often referred to with reference to their corresponding axes of the external reference coordinate system. To this end, in the following the terms North-South axis/direction (e.g. normal axis) are used to refer to the North-South
20 axis/direction in the external reference (orbit) coordinate system and/or to the corresponding North-South body axis/direction of the satellite (which is typically defined as the Y body axis). In the same manner, the Nadir-Zenith axis/direction (e.g. radial axis) and/or the East-West axis/direction (e.g. tangential/longitudinal axis) are used to refer to these axes in the external reference coordinate system and/or to their
25 corresponding body axes in the satellite (which are typically also defined as the Z body axis and X body axis respectively). Since inclination corrections require the major part of the total delta-V budget of the satellite (about 20 times that required for other orbit corrections), in some cases, where applicable, thrusters more efficient than chemical propulsion thrusters, such as electric thrusters (e.g. ion/plasma propulsion thrusters), are
30 used instead of chemical propulsion thrusters.

Electric propulsion, such as ion/plasma thrusters, utilizes electrical power generated by the solar cells of the satellite to supply energy to a propellant to generate thrust. In general, ion thrusters possess a high specific impulse, making them extremely

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efficient, requiring very little propellant for the impulse produced. For example, with the same amount of fuel mass, an ion propulsion system can achieve a final velocity as much as five to ten times higher than that obtainable with a chemical propulsion system.

Currently, electric thrusters which are about five times more efficient than
5 chemical propulsion, are commonplace, providing specific thrust of about 1500 sec versus about 300 sec provided by chemical propulsion thrusters. The advent of the much more efficient electric propulsion systems has permitted attaining the mission lifetime requirement with larger payloads, which are installed on geostationary satellites with the help of a suitable launcher.

10 Typically, when chemical propulsion thrusters are used on the north and/or south panels, they are installed such that the thrust is provided with small or no cant angles (i.e. with thrust cant angles not exceeding a few degrees with respect to the north/south direction; e.g. about 7° and typically not exceeding 10°). Several thrusters may be placed on the north/south panels and may be arranged/tilted such that the impact
15 of the thrusters' exhaust plumes on solar arrays (which are in general placed on these panels) is minimized, but without too much tilt, in order that the effective thrust in the north/south direction is not reduced significantly by the thrust angle.

Use of electrical propulsion thrusters (e.g. ion/plasma thrusters), and the installation of several thrusters on the north/south panels, as in traditional
20 configurations, is less practical. This is due to the fact that in a chemical propulsion system, the thrusters constitute only nozzles and tubing, while in a plasma propulsion system a thruster unit is far more complicated, heavier and more costly. Thus, with plasma propulsion, fewer thrusters (e.g. one or two) are installed at the north/south panels generally at large cant angles (e.g. in the order of 20° - 40°). Such large cant
25 angles are in general not desirable, however they arise from installation constraints due to the presence of solar arrays in such a way that although most of their thrust is in the north/south direction providing inclination control, significant thrust is also applied in the radial (zenith/nadir) direction (it is generally not applicable/desirable to have large components in the tangential direction, as this would throw the spacecraft out of its
30 longitudinal slot, however having relatively small tangential components is possible).

In fact, the cant angle of the thruster from the north/south direction may also affect/perturb one or more in-plane orbit parameters of the satellite (namely the eccentricity and/or the longitudinal position and/or longitudinal drift velocity (tangential

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velocity). In a known eccentricity control concept, these effects are cancelled out by using complementary operations of at least four inclination correction thrusters, two of which are installed with appropriate cant angles as to obtain an east coupling, and the other two, to obtain a west coupling. Alternatively, in another scheme, the effect of the
5 thrust on the in-plane orbit parameters is compensated/cancelled during in-plane maneuvers carried out for example by the east/west thrusters, which may be chemical or electrical.

The inventors of the present invention found that electric thrusters which are installed on the north/south panels with large cant angles in the radial direction (for
10 example in the order of 20° or more; e.g. 30°), can be effectively used for controlling the eccentricity of the orbit. Considering the fact that in certain missions the eccentricity corrections may require several times the ΔV needed for longitude drift corrections in the same period, an optimized design could assign the task of eccentricity keeping to the more efficient electric propulsion system and restrict the chemical thrusters' activation
15 exclusively for the longitude keeping task. Furthermore, such a concept increases the redundancy of the propulsion system. Advantageously, instead of "wasting" the thrust components provided by such thrusters in the radial direction, these are used, according to the technique of the present invention, to compensate/correct drifts in the in-plane parameters of the orbit. To this end, the present invention provides a novel technique for
20 using north and south electric thrusters to achieve inclination corrections as well as in-plane orbit control corrections (e.g. eccentricity control maneuvers). In this concept, the inclination control and in-plane orbit corrections are achieved simultaneously by the same activation(s) of the thrusters.

This is achieved by operating both the north and the south electrical thrusters,
25 which are directed for exerting thrust in the north and south directions as well as in the radial direction, to provide predetermined delta-Vs at predetermined respective sidereal times/angles which are determined in accordance with the required inclination correction $\Delta \vec{i}$ and the required orbit eccentricity correction $\Delta \vec{e}$. To this end, by activating the north and the south thrusters in a certain proportion and at certain timings,
30 eccentricity is controlled in addition to inclination control.

Thus the present invention provides for correcting/adjusting inclination and eccentricity of the satellite's orbit by performing two or more inclination maneuvers in somewhat not optimal timings (non optimal sidereal angles), as compared to the optimal

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timings/sidereal angles conventionally used for inclination corrections, and/or with thrusts delta-V's that are divided properly between the north maneuver and the south maneuver (generally divided differently from the conventional division of the thrust delta-Vs, so as to also provide an eccentricity correction).

- 5 In this regard it should be noted that the phrases optimal timings and optimal sidereal angles referred to above and below correspond to the sidereal angle at which a conventional inclination correction maneuver is conventionally executed to correct the inclination by a required overall inclination correction $\vec{\Delta i}$. The optimal timing/sidereal angle for correcting the overall inclination by correction $\vec{\Delta i}$ corresponds to the sidereal
- 10 angle along the orbit which is perpendicular to the direction of the desired overall inclination correction. For instance, when the required overall inclination correction is directed parallel to the inertial X axis, $\vec{\Delta i} = [i_x, 0]$ then the optimal timing/sidereal angle corresponds to the location at which the orbit intersects the inertial Y axis (namely it is on the inertial Y axis), and vice versa. Conventionally the inclination
- 15 correction maneuvers are performed at optimal timings at which the satellite is located at the optimal sidereal-angles along the orbit to thereby minimize the arithmetic sum of the ΔV 's of the 2 or more maneuvers optimizing the propellant consumption required for the overall inclination correction. Since the main trend of the inclination vector drift is in the ix axis direction, the maneuvers are needed mainly to change the inclination in
- 20 the opposite direction, which is the $-ix$ direction. Such effect is obtained by conducting a south maneuver at the $+Y_i$ axis or alternatively a north maneuver at the $-Y_i$ axis. However, the inclination vector drifts also in the iy direction which makes it necessary to execute inclination maneuvers that are not exactly at the Y_i axis. The above referred to drift in iy is season dependent: during certain months it is in the $+iy$ direction, and
- 25 then during other subsequent months it is in the $-iy$ direction, almost cancelling the previously accumulated $+iy$ component, so in the common case of an inclination keeping requirement of $i < 0.05^\circ$, it is not necessary to compensate for the short term drift in iy . There is however a long term iy drift, also called the secular drift in iy , which still requires active compensation. The optimal sidereal angle for dealing with the iy
- 30 secular drift component is calculated with the help of computer codes that take into account the inclination drift corresponding to the mission years and the size of the inclination station keeping window. Such an algorithm is described in the *Handbook of Geostationary Orbits*, E. M. Soop, Kluwer Academic Publishers, 1994, on page 162.

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The output of this kind of algorithm is characterized by the sidereal angles of the north maneuvers being separated from those of the south maneuvers by 180° . An additional characteristic of the results is that the distribution of ΔV 's between the various maneuvers is not determined, and it is common to use a uniform distribution, i.e. the same ΔV is obtained in each maneuver.

Indeed the use of the non-optimal timings may result in reduced efficiency and/or losses. However these losses are in general relatively very small and the technique of the present invention provides a cost effective way for correcting both the inclination and the eccentricity of a satellite's orbit.

As already mentioned, the technique of the present invention may be implemented also in a satellite which has the ability to perform in plane maneuvers by using its east/west thrusters. In this case, the technique of the invention provides redundant capability to perform in-plane maneuvers even in cases where east/west thrusters are absent and/or malfunction (e.g. due to lack of fuel). This may permit to extend the mission lifetime of various satellites in various scenarios in which the in-plane correction thrusters are inoperable.

The present invention can be invaluable also for a configuration having inclination correction thrusters installed at determined angles as to produce both radial and tangential force components. In nominal operation, such a configuration uses the same thrusters for the task of keeping the inclination, the eccentricity and the longitude within the required limits. However, in case part of the thrusters cannot be activated, the eccentricity control may be severely impaired, and recalculation of the maneuver timings, in accordance with the present invention, may provide a solution to the problem.

Thus a broad aspect of the present invention provides a method for maneuvering a satellite. The method includes: performing two or more complementary north and south maneuvers to adjust an inclination $\vec{i}$ of an orbit of a satellite, by respectively operating north and south thrusters of the satellite, which are respectively installed at panels of the satellite with respective cant angles from the north-south axis. Each of the two or more maneuvers, indexed j , generates respective thrust delta-Vs, thus respectively accelerating the satellite by two or more predetermined supplemental velocities $\{\Delta V^{(j)}\}$ at two or more corresponding sidereal angles $\{S_b^{(j)}\}$ along the orbit. The method of the invention is characterized in that at least one of said sidereal angles

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$\{S_b^{(j)}\}$ of the maneuvers is shifted, to increase or decrease it, with respect to the optimal sidereal angle for performing inclination correction maneuvers (which is generally perpendicular to the desired inclination correction $\Delta\vec{i}$ and is typically near the inertial Y axis) and thereby adjusting said inclination $\vec{i}$ of the orbit by desired inclination
 5 correction $\Delta\vec{i}$ while adjusting additional in-plane parameters by desired in-plane corrections including adjusting at least an eccentricity $\vec{e}$ of the orbit by a desired eccentricity correction $\Delta\vec{e}$.

According to some embodiments of the present invention, the satellite is a geostationary satellite, and the adjustment of the inclination and of the in-plane
 10 parameters of the orbit, including at least said eccentricity $\vec{e}$ of the orbit, are required for station-keeping of said satellite.

According to some embodiments of the present invention the north and south thrusters are electrical thrusters installed at a cant angles from the north-south thus providing a thrust vector having a component directed parallel to a north-south axis, and
 15 a component directed within the plane of the orbit. For instance the in-plane thrust component may include a component in the radial direction and a component in the tangential direction of said orbit. In some cases, the in-plane thrust component is constituted by a substantial thrust component in the radial direction thereby providing adjustment of the eccentricity e of the orbit while having negligible or no effect on in-
 20 plane longitudinal parameters of the satellite.

According to some embodiments of the present invention the magnitudes of each one of the two or more supplemental velocities $\{\Delta V^{(j)}\}$ and the shifting of the at least one sidereal angle $\{S_b^{(j)}\}$, with respect to said optimal sidereal angle, are determined based on the desired inclination corrections $\Delta\vec{i}$ and the desired in-plane
 25 corrections (e.g. the desired eccentricity correction $\Delta\vec{e}$) in such a way that performing the two or more maneuvers adjust the inclination $\vec{i}$ of the orbit by the desired inclination correction $\Delta\vec{i}$ and additionally adjust the eccentricity $\vec{e}$ by the desired eccentricity correction $\Delta\vec{e}$. In some cases the desired in-plane corrections further include longitude drift correction $\Delta\vec{L}$ that is required for correcting the longitudinal drift $\vec{L}$ of the satellite
 30 along the orbit and the supplemental velocities $\{\Delta V^{(j)}\}$ and corresponding nominal sidereal angles $\{S_b^{(j)}\}$ of the two or more maneuvers are configured to also adjust the longitudinal drift $\vec{L}$ by the longitude drift correction $\Delta\vec{L}$.

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According to some embodiments the method of the present invention includes providing data indicative of the desired inclination correction $\Delta \vec{i}$ and the desired in-plane corrections. This data is used to determine the two or more supplemental velocities $\{\Delta V^{(j)}\}$ and the two or more corresponding nominal sidereal angles $\{S_b^{(j)}\}$ of the maneuvers.

In some embodiments of the present invention the two or more maneuvers include, or are constituted by, two complementary north and south correction maneuvers respectively performed by operating the north and south thrusters of the satellite at respective nominal sidereal angles $\{S_b^{(N)}, S_b^{(S)}\}$ to accelerate the satellite by north and south supplemental velocities $\{\Delta V^{(N)}, \Delta V^{(S)}\}$ which are mainly directed in corresponding north and south directions. For instance, in some cases the time at which the north inclination correction maneuver is performed, corresponds to the satellite's location $Sb^{(N)}$ within an arc of the orbit in the angular range of $[-30^\circ, +30^\circ]$ about the negative direction of the inertial Y axis, and the time at which the south inclination correction maneuver is performed, corresponds to the satellite's location $Sb^{(S)}$ within an arc of the orbit in the angular range of $[-30^\circ, +30^\circ]$ about the positive direction of said inertial Y axis. In some embodiments the method of the invention includes adjusting a ratio R between said north and south supplemental velocities $\{\Delta V^{(N)}, \Delta V^{(S)}\}$, to thereby provide desired correction Δe_x to the eccentricity of the satellite's orbit along the inertial X axis e_x . Alternatively or additionally in some embodiments the method of the invention includes decreasing or increasing at least one of the sidereal angles $\{Sb^{(N)}, Sb^{(S)}\}$, at which the north and south inclination correction maneuvers are performed with respect to the optimal sidereal angle (e.g. with respect to the inertial Y axis) to thereby provide desired correction Δe_y to the eccentricity of the satellite's orbit along the inertial Y axis.

According to some embodiments of the present invention, the north and south thrusters are installed at the cant angles θ from the north-south axis such that their thrusts include a thrust component parallel to the north-south axis and a thrust component in the plane of the orbit directed substantially exclusively in the radial direction. Generally the cant angles of the thrusters may be same/similar cant angles or different cant angles.

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In certain embodiments the method of the present invention further includes at least one of the following:

(a) Determining a value of at least one of the X and Y components Δi_x , Δi_y of the inclination required correction vector $\Delta \vec{i}$ in accordance with at least one of a station keeping and a co-location policy of the satellite so as to compensate for the general trend of drift of the inclination $\vec{i}$ of the orbit;

(b) Determining a value of at least one of the X and Y components Δe_x , Δe_y of the eccentricity required correction vector $\Delta \vec{e}$ in accordance with at least one of a station keeping and a co-location policy of the satellite such that said eccentricity correction vector $\Delta \vec{e}$ provides at least partial compensation for the natural drift of the eccentricity $\vec{e}$;

(c) Determining a value of Δe in accordance with a station keeping policy of the satellite so as to restrict longitude daily librations of said satellite to below a certain predetermined threshold;

In some embodiments of the present invention at least one of the north and south thrusters of the satellite has a predetermined respective thrust (e.g. predetermined/fixed thrust power when activated). In such cases the method may further include:

- utilizing data indicative of the respective thrust value of the north and/or south thruster to determine two or more sidereal arcs $\{\Delta S_b^{(j)}\}$ along the orbit corresponding to two or more maneuvers and at which said at least one of the north and south thrusters should be operated to execute a respective maneuver (j); and
- operating the at least one of a north and south thruster along said two or more sidereal arcs $\{\Delta S_b^{(j)}\}$ to thereby effectively accelerate said satellite by said predetermined respective supplemental velocities $\{\Delta V^{(j)}\}$ at said nominal sidereal angles $\{S_b^{(j)}\}$.

For instance, in some embodiments, the nominal sidereal angles $\{S_b(j)\}$ are at the middle of their respective sidereal arcs $\{\Delta S_b(j)\}$, and the lengths of the sidereal arcs $\{\Delta S_b(j)\}$ are determined in accordance with the following: respective supplemental velocities $\{\Delta V(j)\}$ to be supplemented to satellite velocity during a corresponding (j) maneuver, the predetermined thrust (force/power) provided by a respective one of the north and south thrusters used in the corresponding (j) maneuver, the mass of said

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satellite, and the date in which the orbital correction is executed (the date is associated with the direction of eccentricity drift caused by solar radiation pressure).

It should be noted that the method of the present invention as described above and further described in more detail below may be actually implemented in the form of
 5 a computer readable code (instructions) tangibly embedded and stored in a computer readable medium/device. Therefore another broad aspect of the present invention relates to a computer readable device storing computer readable code for carrying out the method as described above and further described below.

According to yet another broad aspect of the present invention there is provided
 10 a control system for maneuvering a satellite. The control system includes: a maneuvering controller (e.g. maneuvering processor) configured and operable for determining maneuvering data indicative of two or more complementary north and south maneuvers, indexed j , to be performed by north and south thrusters of a satellite. The maneuvering controller (hereinafter also referred to interchangeably as
 15 maneuvering processor) is adapted to obtain data indicative of the cant angle(s) of the north and/or south thrusters with respect to a north-south axis, and data indicative of desired orbital corrections including desired inclination correction $\Delta \vec{l}$ for adjusting an inclination $\vec{l}$ of an orbit of said satellite at least one in-plane correction including at least a desired eccentricity correction $\Delta \vec{e}$ for adjusting an eccentricity $\vec{e}$ of the orbit and
 20 process said data to determine thrust delta-Vs $\{\Delta V^{(j)}\}$ indicative of respective accelerations of said satellite during said two or more complementary maneuvers and corresponding sidereal angles $\{S_b^{(j)}\}$ along the orbit at which to respectively perform said two or more complementary maneuvers to obtain said desired orbit corrections. According to the invention the maneuvering processor is adapted to obtain adjustment
 25 of said at least one in-plane parameter of the orbit in addition to adjustment of the inclination of the orbit by determining a shift of at least one sidereal angle $S_b^{(j)}$ of the sidereal angles $\{S_b^{(j)}\}$ of the maneuvers with respect to the optimal sidereal angle (which is generally perpendicular to the desired inclination correction $\Delta \vec{l}$ and is typically near the inertial Y axis), such that the at least one sidereal angle $S_b^{(j)}$ is increased or
 30 decreased with respect to the optimal sidereal angle and thereby provides for adjusting at least the eccentricity $\vec{e}$ of the orbit by the desired eccentricity correction $\Delta \vec{e}$ in addition to the adjustment of the inclination $\vec{l}$.

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In some embodiments of the present invention the control system includes an orbit correction data provider configured and operable for providing the maneuvering processor with orbit correction data including data indicative of the inclination and eccentricity corrections, $\Delta \vec{i}$ and $\Delta \vec{e}$, required for station-keeping of said satellite in a geostationary orbit.

In some embodiments of the present invention the control system is configured and operable for determining said thrust delta-Vs $\{\Delta V^{(j)}\}$ and the sidereal angles $\{S_b^{(j)}\}$ of the two or more complementary maneuvers to further adjust a longitudinal drift $\dot{L}$ of the satellite along the orbit by desired longitude drift correction $\Delta \dot{L}$.

Some embodiments of the control system of the present invention further include a thrusters' controller module adapted to operate the north and/or south thrusters of the satellite in accordance with the maneuvering data to perform the two or more complementary maneuvers and thereby adjust the inclination and eccentricity of the satellite.

It should be noted, and also described in more detail below that in various embodiments of the present invention the control system is configured and operable for implementing various features of the method of the present invention as described above.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to better understand the subject matter that is disclosed herein and to exemplify how it may be carried out in practice, embodiments will now be described, by way of non-limiting examples only, with reference to the accompanying drawings, in which:

Fig. 1A is a general graphical illustration of a satellite in an orbit presented in a Mean Equatorial Geocentric System of Date (MEGSD) quasi-inertial coordinate system;

Fig. 1B is a schematical illustration of a thruster arrangement in a satellite;

Fig. 2A is a flow chart of a satellite maneuvering method according to an embodiment of the present invention;

Fig. 2B is a block diagram schematically illustrating a satellite maneuvering system according to an embodiment of the present invention;

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Figs. 3A to 3C are graphical illustrations respectively showing a 2D inclination vector of a satellite orbit with components i_x and i_y , its natural development, and the effects of an inclination correction maneuver on it, presented in an MEGSD coordinate system;

5 **Fig. 3D** graphically illustrates the annual path of the eccentricity vector development, in natural conditions and under co-location constraints.

Figs. 3E and 3F are graphical illustrations showing the influences of tangential and radial thrusts on the eccentricity vector;

10 **Figs. 4A to 4B** graphically illustrate respectively complementary south and north inclination correction maneuvers according to conventional techniques having zero net effect on eccentricity;

15 **Figs. 5A to 5C, 6A to 6C, and 7A to 7C** graphically exemplify couples of complementary south and a north inclination correction maneuvers according to an embodiment of the present invention, and their net accumulated effect on the orbit's eccentricity in the Y direction, in the X direction and in both X and Y directions respectively;

20 **Figs. 8A to 8C** graphically exemplify three complementary pairs of daily south and north maneuvers performed according to an embodiment of the present invention maneuvers to be performed in the summer and autumn for correcting the satellite's inclination and the effects of the sun's pressure on eccentricity.

DETAILED DESCRIPTION OF EMBODIMENTS

25 Reference is made together to **Figs. 1A and 1B** graphically illustrating schematically a satellite **SAT** along an orbit **ORB**. **Fig. 1A** is a graphical representation of a satellite's orbit **ORB** in the *Mean Equatorial Geocentric System of Date* (MEGSD) reference frame (see *Handbook of Geostationary Orbits*, E. M. Soop, Kluwer Academic Publishers, 1994, page 15).

30 MEGSD is used in the figures and is described in the following to depict the satellite's orbit and orbital parameters. Briefely, the MEGSD reference frame is an Earth-centered (geocentric) inertial (ECI) coordinate frame having three orthogonal X, Y and Z axes with their origin at the center of the mass of the Earth. The Z axis

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(perpendicular to the plane of the figures) coincides with the Earth's rotation axis, the X and Y axes lying in the equatorial plane, and the positive direction of the X axis points to the Vernal Equinox (which is the intersection of the ecliptic plane with the equatorial plane). The reference frame is quasi-inertial with respect to inertial space (does not
 5 rotate together with the Earth) and is not inertial *per-se* where the main difference from an inertial system being the precession of the equinoxes and the acceleration of the Earth itself as it orbits the sun. MEGSD coordinates are used in the following figures for presenting flight dynamics of satellites (e.g. geostationary satellites) and may be for this purpose assumed to be inertial without adverse effect. For clarity, the south and north
 10 directions, the negative and positive directions of the Z axis, are designated in the figures by **S** and **N**, and marked with corresponding signs designating *in-to-* and *out-of-* the figure plane. Satellite **SAT** is shown in the orbit with tangential velocity **V_T** and positioned along the orbit at a certain sidereal angle **S_b**. The sidereal angle **S_b**, which relates directly to time, is measured from the **X** coordinate of the MEGSD. Satellite
 15 centered radial and tangential coordinates are also used in the following to describe satellite flight dynamics. These are depicted in the figures by the radial *nadir* and *zenith* directions, **Nr** and **Zt** respectively point towards and away-from the center of mass of the Earth, and the east and west directions, designated **E** and **W** respectively, each point to opposite tangential directions along the satellite's orbit **ORB**.

20 **Fig. 1B** is an illustration exemplifying a configuration of a conventional satellite **SAT**. Here, for clarity, the satellite is illustrated as a box. The satellite's center of mass is designated **CM** and the north, west and zenith panels/sides of the satellite **SAT** are designated by **NP**, **WP**, and **ZP**. Also shown are the north, west and zenith thrusters **NT**, **WT**, and **ZT** installed on the respective panels. Complementary thrusters (e.g. in
 25 the south, east and nadir directions/panels) may also be present on the satellite although these are not explicitly shown in the figure. The west and zenith thrusters, **WT** and **ZT**, are installed so as to provide respectively delta-Vs, **T-E** and **T-Nr**, in the east and nadir directions **E** and **Nr** illustrated in **Fig. 1A**. The thruster **NT** is exemplified here being furnished with cant angle θ on the north panel **NP**, thus providing thrust **T-S** angled by
 30 θ with respect to the south direction **S**. Therefore, in addition to thrust component in the south direction, the thrust **T-S** may also have component(s) in the radial (nadir-zenith) and/or in the tangential (east-west) axes. Although not explicitly shown in the figure, complementary thrusters (e.g. in the south, east and nadir directions/panels) may also be

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present on the satellite and may be arranged for example to provide delta-Vs directed opposite to thrusts **T-S**, **T-E** and **T-Nr**. To this end also the **T-N** in the north direction may also have component(s) along the radial and/or the axes.

Fig. 2A shows a flow chart **200** of a method used in some embodiments of the present invention to maneuver a satellite so as to adjust its orbit inclination $\vec{i}$ and at least one additional orbit parameter, which may be one or more of the following: the orbit's eccentricity $\vec{e}$, and the longitudinal drift velocity $\dot{L}$ of the satellite. In general, the longitudinal drift velocity $\dot{L}$ relates and can be determined by the orbit's semi-major axis a , eccentricity $\vec{e}$, and sidereal angle S_b in the orbit.

Operation **210** of method **200** includes provision of *orbit correction data* indicative of desired orbit corrections to be applied to the satellite orbit. The *orbit correction data* includes data indicative of desired inclination correction $\Delta\vec{i}$ and also data indicative of desired corrections to at least one additional orbit parameter, being one of the following: (i) desired correction $\Delta\vec{e}$ to one or more components of the eccentricity $\vec{e}$ vector of the orbit; and (ii) longitudinal drift velocity correction $\Delta\dot{L}$ for adjusting the longitudinal drift velocity (data indicative of (ii) may be provided in terms of the sidereal angle position of the satellite and/or the tangential velocity thereof).

Operation **220** includes providing *satellite configuration data* indicative of cant angles θ_N and θ_S of the north and south electrical thrusters of the satellite (for clarity and without loss of generality in the following, similar north and south cant angles may be considered designated by θ where $\theta = \theta^N = \theta^S$). The cant angles may be used to determine the part/portion of thrust, which is provided by each of the north and south electrical thrusters along the north-south (Z) axis and the part/portion of the thrust directed to the radial (nadir-zenith) and/or tangential (east-west) directions.

Preferably, method **200** is performed in satellites having electrical north and/or south thrusters, because such thrusters are highly efficient and are typically installed with relatively large cant angles (e.g. more than 20° from the north-south axis). Accordingly in this case the amount of thrust directed to the radial and/or tangential directions by the north and/or south thrusters may suffice for efficiently correcting the eccentricity and/or longitudinal drift of the satellite.

In general, electrical propulsion satellites have fewer thrusters than those with chemical propulsion. This is due to the increased mass and cost of such thrusters, which

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are installed as propulsion units, in contrast to the mass and cost of adding nozzles and tubing, as in the case of chemically propelled satellites. Therefore, it is common to assign the inclination keeping task to the more efficient electrical thrusters, while leaving the longitude drift control and the angular momentum unload to a more simple, light and less costly form of propulsion, such as Bi-propellant, Hydrazine or even cold-gas systems. The minimalistic electrical propulsion concepts have their north and south thrusters installed in the y-z plane, in order to have only a very small residual force component in the tangential east-west (E/W) direction. Those propulsion concepts typically have only one thruster in each of the north and/or south faces, which means that they would be better installed parallel to the y axis and would pass through the average center of mass (COM) of the satellite. However, installing the north and/or south thruster in this direction is typically not viable, due to the presence of solar-arrays. The north and/or south thrusters are therefore often installed not at the mean COM in the z (north-south) coordinate, but at a significantly different z coordinate. As a consequence, the thrusters/thrust line/direction thereof is given a deflection (cant) angle in order to guarantee that the force line passes sufficiently close to the COM, thus causing only low levels of angular momentum which can be absorbed by reaction wheels installed in the satellite. Therefore, it is common when dealing with electrical propulsion, that the relatively large cant angles at which electrical north and/or south thrusters are installed, yield large values of east-west (E/W) and/or north-south (N/S) couplings. The cant angle indeed causes a decrease in the effective efficiency of the north and south thrusters, but this is more than compensated for by the increased electrical propulsion Isp which can be as much as 5-fold the efficiency of chemical propulsion. It is noted here that the expression *effective efficiency* relates to the propulsion efficiency of the thrusters in the N/S directions which is reduced by a factor of $1-\cos(\theta)$ and not to the efficiency of the thrusters themselves, which is not affected.

Operation **230** of method **200** includes utilizing the *orbit correction data* and the *satellite configuration data* and determining maneuver parameters $MP^{(j)}$ of one or more maneuvers to be performed by the north and south thrusters of the satellite in order to adjust the satellite's inclination and the at least one additional orbit parameter in accordance with the *orbit correction data* provided in **210** (herein above and in the following, the upper index (j), put in parentheses, designates specific maneuver). The maneuver parameters $MP^{(j)}$ of each maneuver (j) include at least: (a) delta-V parameter

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$\Delta V^{(j)}$ (hereinafter also referred to as supplemental velocity and/or thrust delta-V) indicative of the change in the velocity of the satellite during the s maneuver; (b) corresponding nominal times $\{Sb^{(j)}\}$ along the orbit at which the respective delta-V $\Delta V^{(j)}$ of the corresponding maneuver should be exerted; (c) indication of which
 5 thruster(s) should be activated in the maneuver (e.g. specifically, whether the north and/or the south thrusters should be activated). The last parameter may be implicit (e.g. associated with the maneuver being a north or a south maneuver) and/or it may be inherently indicated by the $\Delta V^{(j)}$ parameter of the maneuver, in case it is provided in vector form (also designating the direction of the thrust).

10 In general, operation **230** is aimed at determining the maneuver parameters which will effectively exploit the cant angles of the north/south electric thrusters (the thrust components which are therefore provided by those thrusters in the radial/tangential directions) in order to correct the one or more additional orbit parameters indicated above. It is understood that thrust components in radial and/or
 15 tangential directions may be used to correct /modify the eccentricity of a satellite orbit and its longitudinal drift velocity. Indeed conventionally, one or more south and/or north maneuvers are performed by north/south thrusters of a satellite to correct the inclination. Yet according to the technique of the present invention, since the north/south thrusters also provide thrust components in radial and/or tangential
 20 directions, the maneuver parameters of the north and south maneuvers are selected/determined such that these thrust components (which are perpendicular to the north-south axis) from north/south maneuvers, are combined to carry out the desired adjustment to the eccentricity and/or longitudinal drift velocity.

To this end, each maneuver by the south or north thruster is associated with two
 25 degrees of freedom: the thrust delta-V, being the ΔV speed imparted to the satellite during the maneuver, and the nominal sidereal angle S_b at which the maneuver is performed. Accordingly, an inclination correction $\Delta \vec{i}$ defined by two vector components, i_x, i_y , can be achieved by proper adjustment of the two degrees of freedom ΔV and S_b of a single maneuver executed by the north and/or south thrusters. Yet, according to the
 30 present invention, in cases where the north/south thrusters are installed with cant angles towards the radial and/or tangential directions (which are usable for eccentricity and/or longitudinal drift corrections), the degrees of freedom of two or more maneuvers are

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used to correct the inclination $\vec{i}$ of the orbit and in addition to correct one or more additional in-plane orbit parameters (e.g. e_x , e_y , and/or $\dot{L}$).

For example, considering a pair of north and south maneuvers, designated here by index $j \in \{N, S\}$, the degrees of freedom of these maneuvers: $\Delta V^{(N)}$, $S_b^{(N)}$, $\Delta V^{(S)}$ and $S_b^{(S)}$ can be adjusted according to the present invention to correct the inclination and the eccentricity, namely: i_x , i_y , e_x , e_y .

To this end, consider for example a case where the thrusters are installed with similar cant angles directed such that the thrusters provide a thrust component in the radial direction in addition to the thrust component in the north/south direction. In such a case, in a first approximation, the operation **230** may be carried out for setting the magnitude $|\Delta \vec{i}|$ of the inclination correction by determining the total thrust delta-Vs, $\Delta V^{(S)} + \Delta V^{(N)}$ to be provided by both maneuvers, the direction $\Delta \vec{i} / |\Delta \vec{i}|$ of the inclination correction may be set by suitable selection of the weighted mean $(\Delta V^{(N)} S_b^{(N)} + \Delta V^{(S)} S_b^{(S)}) / (\Delta V^{(N)} + \Delta V^{(S)})$ of the sidereal angles of the north and south maneuvers weighted by their respective thrust delta-Vs correcting the Y component e_y of the eccentricity may be achieved by advancing and/or retarding the sidereal angles of the north and/or south maneuvers $S_b^{(N)}$ and $S_b^{(S)}$, and correcting the X component e_x of the eccentricity may be achieved by proper selection of the proportion ratio R between the thrust delta-Vs of these maneuvers, $R = \Delta V^{(N)} / \Delta V^{(S)}$.

In a similar way, the degrees of freedom, $\Delta V^{(N)}$, $S_b^{(N)}$, $\Delta V^{(S)}$ and $S_b^{(S)}$, of one or more such north and south maneuvers can be adjusted/selected according to the present invention to also correct the longitudinal drift speed $\dot{L}$ in addition to the inclination and eccentricity corrections. For example, consider a case where the thrusters are installed with similar cant angles directed such that they provide a thrust component in the tangential direction (e.g. east) in addition to thrust in the north/south direction. In this case, in **230** as in the above example, the total thrust delta-Vs and the weighted mean of the sidereal angles may be set to provide desired inclination correction $\Delta \vec{i}$. Also, in a first approximation, the desired change $\Delta \dot{L}$ in the longitudinal drift velocity may be set in **230** by determining a proper difference $\Delta V^{(N)} - \Delta V^{(S)}$

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between thrust ΔV s of the maneuvers (the tangential components of both thrusters are in the same direction, e.g. east).

The technique of the present invention is relevant for satellites in which the inclination correction thrusters are installed with cant angles which are sufficiently large
 5 for providing the necessary radial and/or tangential thrusts for executing the desired in-plane corrections (e.g. cant angles being not below 15° and preferably above 20°). To this end, a person of ordinary skill in the art knowing the present invention, will readily appreciate how to execute two or more maneuvers by north/south thrusters installed with such cant angles in order to correct the orbit inclination and the in-plane orbit
 10 parameters $\vec{e}$, and $\dot{L}$.

Operation **240** of method **200** prepares the operative instructions **OI** to the satellite (e.g. to be provided to the north and/or south thrusters thereof) for performing the one or more maneuvers determined in **230**. The maneuver(s) are performed such that at each maneuver j one thruster of the north and south electrical thrusters specified
 15 by the maneuver parameters is operated at nominal time $S_b^{(j)}$ (sidereal time/angle) indicated by the maneuver parameters to exert respective thrust $\Delta V^{(j)}$.

Fig. 2B is a block diagram schematically illustrating a satellite system **300** according to an embodiment of the present invention. The satellite system includes a maneuvering control system **302** and a satellite **SAT**. The maneuvering control system
 20 **302** may be an electronic/computerized system configured and operable for carrying out the method **200** illustrated in **Fig. 2A** for maneuvering at least one satellite **SAT** into a desired orbit of selected inclination limits and at least one of a selected eccentricity and/or longitudinal drift-speed of the satellite. The maneuvering control system **302** may be partially/entirely integrated in the satellite, and/or some parts or all of the
 25 maneuvering control system **302** may be located at a remote base/ground station and may be adapted for controlling the thruster's operation via data communication.

As illustrated in the figure, the Satellite **SAT** exemplified here is similar to the satellite illustrated in **Fig. 1B** in the sense that it includes south (not specifically shown) and north **NT** electric thrusters, providing thrusts with cant angles θ from the north-south axis. The satellite **SAT** is connectable to the maneuvering control system **302** and
 30 is adapted to receive from it the operational instructions **OI** for operating the north's

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and/or south's thrusters to maneuver the satellite according to the technique of the invention.

In certain embodiments of the present invention the maneuvering control system **302** includes an *orbit correction data* provider module **310** that is adapted to provide the *orbit correction data* **OCD** indicated above. More specifically it may include data
 5 indicative of desired inclination correction Δi and data indicative of one or more of the following corrections of the additional orbit parameter: Δe_x , Δe_y , ΔL , and $\Delta \dot{L}$ (the latter, ΔL and $\Delta \dot{L}$, may be indicated by a desired change in the angular position S of the satellite along the orbit and/or a change in its tangential velocity V_T).

10 To this end the *orbit correction data* provider **310** may include a data link **312** configured and operable for providing the orbit correction data **OCD**. The term *data-link* is used herein to designate, generically, any type of data provision technique, e.g. from a user interface data input module, from local/remote data sources/repositories, such as files and databases, and/or data communication connection capable of obtaining
 15 data from such remote/local data sources, which may be internal/external to the system. Data link **312** is configured for receiving the required orbit correction data **OCD** from one or more predetermined data sources.

Alternatively or additionally, the *orbit correction data* provider **310** may include an orbit correction processor **314** (e.g. analogue and/or digital processing system) that is
 20 adapted for receiving data indicative of the satellite status **SSD** (e.g. the satellite's velocity and location/sidereal-angle at a given time), and process this data together with predetermined **SKD** data relating to the desired operation of the satellite, to thereby determine/compute the orbit correction data **OCD**.

In certain embodiments of the present invention the satellite **SAT** is a
 25 geostationary satellite and the maneuvers of the present invention are used for station-keeping of said satellite. Accordingly the data **SKD** may be based on a station keeping policy associated with the geostationary station keeping of the satellite. Various techniques for determining the required/desired orbit corrections **OCD** based on the current status (orbit) of the satellite **SSD** (e.g. defined by the satellite's velocity and
 30 location) and the station keeping policy **SKD** are readily known to those versed in the art. To this end, in some cases, the maneuvering control system **302** includes, and/or is connected to, station keeping policy **SKD** data provider (data link - not specifically

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shown in the figure) capable of providing the orbit correction processor **314** with data indicative of the station keeping policy **SKD** for the satellite.

The maneuvering control system **302** may include a satellite state data provider module **340** adapted for monitoring/obtaining at least some parameters of the orbit state
 5 of the satellite, such as the orbit's inclination $\vec{i}$, the orbit's eccentricity $\vec{e}$, the position $\mathbf{S}_b$ of the satellite along the orbit, and/or its tangential velocity V_T . In some embodiments some or all of these parameters are provided to the orbit correction processor **314**, so the latter can determine the required orbit corrections based thereon. The satellite state data provider module **340** may be a local module and/or it may include one or more remote
 10 modules such as antennas or optical detectors capable of detecting the satellite's position and/or speed, by any one or more of various techniques known in the art (including techniques based on Doppler measurements, image processing, global positioning and/or other techniques known to those versed in the art).

The maneuvering control system **302** includes a maneuvering processor **330** (i.e.
 15 maneuvering controller) that is configured and operable for receiving the orbit corrections **OCD** indicating the corrections to be applied to the satellite's orbit, and using data indicative of the satellite's configuration (herein after referred to as satellite configuration data) **SCD**, including in particular data indicative of the cant angle(s) θ at which the north and/or south thrusters are installed, and process the orbit corrections
 20 **OCD** and the satellite configuration data **SCD** to determine maneuvering data $\{\mathbf{MP}^{(j)}\}$ indicative of maneuver parameters such as the thrust delta-Vs $\{\Delta V^{(j)}\}$ that should be activated by the north and/or south thrusters at each maneuver j and the corresponding nominal sidereal times/angles $\{\mathbf{S}_b^{(j)}\}$ at which the maneuvers should be performed. The maneuvering processor/controller may be implemented as a computerized system
 25 including hardware components and/or software components.

In some cases the satellite configuration data **SCD** also include data indicative of the thrust force that the north/south thrusters can provide. Accordingly the maneuvering processor **330** may utilize data on the respective thrust of the north/south thrusters to determine time durations $\{\Delta S_b(j)\}$ (namely the lengths of the orbital arcs) during
 30 which the thrusters should be activated in order to provide the respective thrust delta-Vs $\{\Delta V(j)\}$ required for each maneuver j . This may be determined in accordance with the respective supplemental velocities (delta-Vs) $\{\Delta V(j)\}$ to be supplemented to the

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satellite during the corresponding maneuvers j , the thrust force provided by the corresponding thruster (north or south) used in the maneuver j , the mass of the satellite, and the date (time of year) in which the maneuver is executed (the date relates to the intensity and direction of the radiation pressure due from the sun which affects the eccentricity drift).

As a result, for each maneuver j the maneuver data $MP^{(j)}$ may include data indicative of the initial and final times $S_b^{(j)}{}_I$ $S_b^{(j)}{}_F$ associated with the activation and deactivation of the corresponding thruster used in the maneuver, such that in total during the maneuver j , the thruster supplements the satellite with the desired thrust ΔV . In this regard typically the following relations apply: (1) the mean/nominal sidereal angle $S_b^{(j)}$ at which the maneuver is performed is given by $S_b^{(j)} = (S_b^{(j)}{}_I + S_b^{(j)}{}_F) / 2$; and (2) the duration/sidereal-arc $\Delta Sb^{(j)}$ during which the maneuver takes place is given by $\Delta Sb^{(j)} = (S_b^{(j)}{}_F - S_b^{(j)}{}_I)$. To this end, the initial and final times $S_b^{(j)}{}_I$ $S_b^{(j)}{}_F$ are computed based on the respective thrust such that when activating/ deactivating the thruster at these times respectively, the required equivalent ΔV is provided at the nominal time $S_b^{(j)}$ towards the required direction in space. This allows performing the maneuvers of the present invention by using thrusters, such as electric thrusters, which have relatively low instantaneous power. The process to compute the initial and final times, $S_b^i{}_I$ and $S_b^j{}_F$, of the activation of the satellite thrusters given that it should be activated to supply a given thrust ΔV at a given nominal sidereal time/angle S_b^j would be readily known to those versed in the art.

It should be noted that the satellite configuration data **SCD** may vary from satellite to satellite, as for example the north and south thrusters may be installed with different or same respective cant angles θ_N and θ_S , which may differ from satellite to satellite and/or different thrust powers may be provided by different types/models of thrusters installed in different satellites and/or in different panels of the same satellite. Accordingly the system may optionally include a satellite configuration data provider module **320**, configured and operable for providing the satellite configuration data **SCD** to the maneuvering processor **330**. The maneuvering processor **330** can determine the maneuver parameters based on the actual configuration (cant angles and/or thrusters'

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power) of the satellite being managed. The satellite configuration data **SCD** for a given satellite may be stored in memory and/or it may be hard/soft coded in the system. In cases where the system **302** is configured for managing various satellites, the satellite configuration data provider module **320** may optionally include a satellite configuration data link **322** configured and operable for retrieving satellite configuration data **SCD** to be provided to the maneuvering processor **330**.

Thus, maneuvering processor **330** provides maneuvering data $\{MP^{(j)}\}$ indicative of maneuver parameters (e.g. thrust delta-Vs $\{\Delta V^{(j)}\}$ and nominal timings $\{S_b^{(j)}\}$ for one or more maneuvers (indexed j) that are to be performed by the north and/or the south thrusters in order to correct the inclination and at least one additional orbit parameter of the satellite. The technique of the invention by which maneuvering processor **330** determines the maneuvering parameters that provide for using the south and/or north thrusters to correct both the inclination of the orbit and the additional parameter (eccentricity/longitudinal drift) is described in detail below.

Optionally the maneuvering control system **302** also includes thruster's controller module **360** configured and operable for using the maneuvering data $\{MP^{(j)}\}$ determined by maneuvering processor **330** and using satellite status data **SSD** (e.g. provided from the satellite state data provider module **340**) to generate operational instructions for operating the north and/or south thrusters of the satellite **SAT**, to implement a maneuver according to the present invention. The thruster's controller module **360** utilizes the satellite status data **SSD** to determine when the satellite **SAT** reaches near the nominal times/angles $\{S_b^{(j)}\}$, at which maneuver $MP^{(j)}$ of the maneuvers $\{MP^j\}$ should be performed (e.g. when it reaches the initial $S_b^{(j)}{}_I$ and final $S_b^{(j)}{}_F$ sidereal angles indicated above, and generates operational instructions **OI** to activate a respective one of the north/south thrusters associated with the maneuver $MP^{(j)}$ to exert the thrust $\Delta V^{(j)}$ of the maneuver). More specifically, the operational instructions may include instructions for initiating the operation of the respective north/south thruster when the satellite is positioned at the initial angle $S_b^{(j)}{}_I$ at which the maneuver should commence, and instructions for stopping the operation of the respective north/south thruster the final angle $S_b^{(j)}{}_F$ at which the maneuver should be terminated. Optionally, in cases where thrust of the relevant thruster is variable and

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controllable, the operational instructions may also include data indicative of the thrust that should be exerted during the maneuver. Alternatively or additionally when the thruster is fixed, the initial and final angles $S_b^{(i)}{}_I$ and $S_b^{(i)}{}_F$ are set to provide the desired thrust $\Delta V^{(i)}$.

5 Thus, the method and system of the present invention provide for using north and/or south thrusters of a satellite, which are conventionally used for inclination correction maneuvers, to perform one or more maneuvers for correcting both the inclination and at least one of the eccentricity of the orbit and/or the longitudinal drift velocity thereof.

10 Figs. **3A to 3C** depict, in the MEGSD coordinates, the inclination vector $\vec{i}$ of a satellite, its typical development/drift and typical maneuvers for correcting this drift. The 2D inclination vector $\vec{i} \equiv [i_x, i_y]$ is presented in the MEGSD coordinates. The inclination vector $\vec{i}$ is a projection of the unit vector in the direction of the satellite's angular momentum on the equatorial X-Y plane.

15 **Fig. 3A** shows an instantaneous inclination state $\vec{i}$ of a satellite's orbit. The direction of the inclination vector $\vec{i}$ defines the right ascension of the ascending node angle Ω (the intersection between the orbit and equatorial planes), as follows:

$$\frac{\vec{i}}{|\vec{i}|} = \begin{pmatrix} \sin \Omega \\ -\cos \Omega \end{pmatrix}. \text{ The circumference } \mathbf{MI} \text{ shown in the diagram of represents the}$$

20 maximum inclination $|i|$ permissible for the satellite in order to ensure station keeping of the satellite with respect to the latitude coordinate.

Fig. 3B is a graphical example illustrating the development/drift of the inclination vector of the orbit $\vec{i}$ in time caused by gravitational influences of the moon and the sun. The graphs show the projection of the angular momentum on the X-Y plane in units of degrees (representing the inclination of the orbit with respect to the X and Y axes). The circle **ISK** represents the maximal allowable inclination for station keeping according to the station keeping policy of the satellite (e.g. 0.05°). In the figure, first/initial and second inclination states $\vec{i}_1$ and $\vec{i}_2$ of the orbit are illustrated, describing the initial and end inclination states of the orbit within a time frame of a few weeks. The path **ID** illustrates the drift of the inclination vector from the first to the second states (from $\vec{i}_1$ to $\vec{i}_2$), which is caused by the gravitational forces of the sun and the moon that are applied on the satellite during this time period. As shown in the figure, the main

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trend of this drift is in the direction of the positive X axis. Accordingly, a required inclination correction $\Delta \vec{i}$ to return to the first inclination state $\vec{i}^{(1)}$ will be given by $\Delta \vec{i} = \vec{i}_1 - \vec{i}_2$.

Fig. 3C exemplifies a conventional pair of complementary south and north maneuvers, **SM** and **NM**, for correcting the inclination $\vec{i}$ of the satellite's orbit ORB in the X-Y plane. The graphs show the change in the inclination of the satellite (in units of degrees) as affected by the inclination drift and corrected by the south and north maneuvers, **SM** and **NM**. These south and north maneuvers, **SM** and **NM**, exert delta-Vs of similar magnitudes, and are conducted at sidereal angles (times) being 12 hours apart. Accordingly, these maneuvers provide similar corrections $\Delta \vec{i}/2$ to the inclination vector $\vec{i}$ which add up to the desired inclination correction $\Delta \vec{i}$ shown in the figure, while their total effect on other parameters of the orbit **ORB** is negligible or zero. The south maneuver **SM** is performed by activating the thruster at the north panel to exert thrust delta-V mainly in the south direction, and vice-versa, the north maneuver **NM** is performed by activating the thruster at the south panel to exert thrust delta-V mainly in the north direction.

Fig. 3D illustrates the eccentricity vector $\vec{e}$ of an orbit, and its development in natural and constrained states. The eccentricity $\vec{e}$ is a unit-less 2-dimensional (2D) vector pointing in the direction of the perigee of the orbit (namely to the point at which the satellite is closest to the center of the earth). The magnitude of the eccentricity of the orbit is defined zero for circular orbits and between $0 < e < 1$ for elliptical orbits. Considering the MEGSD coordinates, the 2D eccentricity vector $\mathbf{e}$ may be defined as follows: $\vec{e} = e \begin{pmatrix} \cos(\Omega + \omega) \\ \sin(\Omega + \omega) \end{pmatrix}$ where Ω is the right ascension of the ascending node, ω is the argument of the perigee of the orbit and e is the value/magnitude of the eccentricity.

The outer circumference in the diagram exemplifies a maximum permissible eccentricity values/threshold allowed by a certain station keeping policy in order to ensure longitude station keeping. Path **G1** illustrates a natural development of the eccentricity vector during a time frame of about one year. In other words, **G1** presents a typical long term drift of the eccentricity vector caused by the solar pressure. **G1** is a concentric/spiral-like path (e.g. whose radius increases in time due to an increase in the ballistic coefficient of the satellite). When the eccentricity exceeds maximum

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permissible eccentricity, it yields too large daily longitude librations. Accordingly, eccentricity correction $\overrightarrow{\Delta e}$ may be required to compensate for the increase in the length of the $\overrightarrow{\Delta e}$ caused by the eccentricity drift. As indicated above, conventionally, adjusting the eccentricity is performed by thrusters installed on at least one of the
 5 east/west/nadir/zenith panels of the satellite and providing thrust power to the respective west/east/zenith/nadir directions. In this connection it should be noted that the larger the solar panels/arrays of the satellite, the greater the solar pressure force exerted thereon, and therefore the greater the eccentricity vector radius. Therefore, satellites having/
 heavily relying on electric propulsion (which are typically equipped with larger solar
 10 panels) require that eccentricity correction maneuvers are performed more often and/or with higher delta-Vs.

Figs. 3E and 3F show respectively the influences $\Delta \vec{e}$ of radial and tangential thrust delta-V components, $\Delta \mathbf{V}_{\text{nadir}}$ and $\Delta \mathbf{V}_{\text{east}}$ on the eccentricity vector $\vec{e}$. As shown in **Fig. 3E**, a radial thrust delta-V $\Delta \mathbf{V}_{\text{nadir}}$ in the nadir direction changes the eccentricity in
 15 a direction perpendicular to both the north-south and the radial (zenith-nadir) axes. An opposite radial component $\Delta \mathbf{V}_{\text{zenith}}$ to the zenith would affect $\Delta \vec{e}$ in the opposite direction. As shown in **Fig. 3F**, a thrust delta-V $\Delta \mathbf{V}_{\text{east}}$ in the tangential east direction causes a change in the eccentricity along an axis perpendicular to both the north-south and tangential (east-west) axes. A tangential component $\Delta \mathbf{V}_{\text{west}}$ to the west would affect
 20 $\Delta \vec{e}$ in the opposite direction.

Figs. 4A and 4B are graphical illustrations of conventional inclination correction maneuvers (conventional north and south maneuvers) typically performed with satellites having electrical propulsion north and south thrusters installed with large cant angles (e.g. 30°) with respect to the north/south. As indicated above, in such satellite
 25 configuration, the north/south thrusters, producing delta-V components in the radial/tangential directions, which as exemplified in **Figs. 3E and 3F**, affect the orbit eccentricity (and/or possibly other in-plane parameters of the orbit). Therefore conventional inclination correction maneuvers include two complementary north and south maneuvers (by the south and north thrusters respectively) performed such that the
 30 total thrust delta-V $\Delta \mathbf{V}^{\text{Tot}}$ is directed along the north-south axis (or otherwise such that their effect on the in-plane parameters has vanished/is negligible). In the example of such conventional inclination correction maneuvers illustrated in **Figs. 4A and 4B**, a

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satellite configuration with similar north and south cant angles is considered. The north and south maneuvers are performed with similar thrust delta-Vs which are provided at sidereal angles that are 180° apart. Accordingly, in the south maneuver (**Fig. 4A**) thrust components are provided to the south and nadir directions ΔV_{south} and ΔV_{nadir} ; in the
 5 north maneuver (**Fig. 4B**) the thrust components are provided to the north and nadir directions ΔV_{north} and ΔV_{nadir} . Thus, as shown in the figures, the inclination corrections $\Delta i^{(n)}$ and $\Delta i^{(s)}$ provided by the conventional north and south maneuvers are equal in magnitude and in the same direction and add up to the desired total inclination correction $\Delta i^{(\text{tot})}$. The effects on the eccentricity $\Delta e^{(n)}$ and $\Delta e^{(s)}$ of these maneuvers are
 10 equal in magnitude, but in opposite directions, and are therefore nullified. It is understood that in other cant angle configurations, the thrusts and the sidereal angles of the maneuvers may be adjusted differently to nullify the eccentricity effects $\Delta e^{(n)}$ and $\Delta e^{(s)}$.

On the contrary, as indicated above, according to the technique of the present
 15 invention, thrust components that are not in the north-south direction (due to the cant angle of the thrusters) are exploited to apply the correction to the additional in-plane orbit parameter (being the eccentricity of the orbit and/or longitudinal drift-speed of the satellite).

This may be achieved for example by carrying out north and south maneuvers,
 20 similar to those conventionally used for inclination compensation only, however modifying the maneuvers with respect to the conventional ones by at least one of: (i) advancing and/or retarding the timings $S_b^{(N)}$ and $S_b^{(S)}$ of these north and south maneuvers; and/or (ii) modifying the thrust delta-Vs $\Delta V^{(N)}$ and $\Delta V^{(S)}$ of the north and south maneuvers such that they are not equal. According to the invention, the timings
 25 $S_b^{(N)}$ and $S_b^{(S)}$ and/or the thrust delta-Vs $\Delta V^{(N)}$ and $\Delta V^{(S)}$ are such that their combined vector components along the north/south axis provide desired inclination correction and their combined vector components along radial and/or tangential direction provide desired correction to the in-plane orbit parameters. A few examples of the technique of the invention are illustrated in: **Figs. 5A to 5C**, **Figs. 6A to 6C**, and
 30 **Figs. 7A to 7C**. These figures show three pairs of south and north maneuvers according to the present invention for correcting the orbit inclination $\vec{i}$ by desired inclination

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correction vector $\Delta \vec{l}^{(tot)}$ and correcting eccentricity $\vec{e}$ by desired eccentricity correction vector $\Delta \vec{e}^{(tot)}$.

Figs. 5A and 5B respectively show the effect of south and north maneuvers on the inclination and eccentricity of the satellite in cases where the timings $Sb^{(N)}$ and $Sb^{(S)}$ of the north and south maneuvers are respectively advanced and retarded (i.e. decreased and increased respectively) by a predetermined ΔS angle as compared to a conventional maneuver. **Fig. 5C** shows the combined/total effects, $\Delta \vec{l}^{(tot)}$ and $\Delta \vec{e}^{(tot)}$ of the maneuvers illustrated in **Figs. 5A and 5B** on the inclination and eccentricity of the orbit. As illustrated in **Fig. 5C**, a predetermined/desired eccentricity correction $\Delta \vec{e}^{(tot)}$, directed along the Y axis can be obtained according to the present invention by respectively advancing and retarding the north and south maneuvers by proper ΔS angle(s). To this end, an inclination maneuver conducted not exactly on the Y axis has an effect on the Y component of the eccentricity e_y . As illustrated in **Fig. 5A**, advancing the south maneuver, which provides inclination correction in the $-X$ direction, induces an eccentricity correction component Δe_y in the $+Y$ direction. As illustrated in **Fig. 5B**, the same effect on the inclination in the $-X$ direction is obtained by postponing/retarding the execution of a north maneuver, but here an eccentricity correction component Δe_y in the $+Y$ direction is induced.

Figs. 6A and 6B respectively show the effect of south and north maneuvers on the inclination and eccentricity of the satellite in cases where different magnitudes of the thrust delta-Vs $\Delta V^{(N)}$ and $\Delta V^{(S)}$ are provided by the north and south maneuvers.

Fig. 6C shows the combined/total effects, $\Delta \vec{l}^{(tot)}$ and $\Delta \vec{e}^{(tot)}$ of the maneuvers illustrated in **Figs. 6A and 6B** on the inclination and eccentricity of the orbit. As illustrated in **Fig. 6C**, the different thrust delta-Vs $\Delta V^{(N)}$ and $\Delta V^{(S)}$ can be selected according to the present invention such that an eccentricity correction of prescribed magnitude $\Delta \vec{e}^{(tot)}$ directed along the X axis is obtained in addition to the desired inclination correction $\Delta \vec{l}^{(tot)}$. **Fig. 6A** shows that a south inclination correction $\Delta V^{(S)}$ provides an inclination correction in the $-X$ direction, and also changes the eccentricity vector in the $-X$ direction. **Fig. 6B** shows a complementary north inclination correction $\Delta V^{(N)}$, separated by about 12 sidereal hours from the north inclination correction,

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provides an inclination correction in the $-X$ direction, and has the opposite effect on the eccentricity vector, as it changes the eccentricity vector in the $+X$ direction. As the same effect on the inclination can be obtained either conducting a north or a south maneuver, the proper proportion between these two maneuvers represents a degree of freedom,
 5 providing for adjusting the eccentricity by Δe_y in the $\pm X$ directions.

It should be noted that the control/adjustment of the eccentricity component e_x has generally no, or only minor, impact on the propellant consumption (e.g. it does not practically reduce the efficiency of the inclination correction maneuver), since it involves only proper division of the thrust delta-Vs between the north and the south
 10 maneuvers. On the other hand, controlling/adjusting the eccentricity component e_y may increase the propellant consumption (namely it may reduce the efficiency of the inclination correction maneuver) since it is achieved by executing the inclination correction maneuvers at somewhat non-optimal timings (sidereal angles). In fact, advancing/retarding the timings, $Sb^{(S)}$ and $Sb^{(N)}$, of the south and north inclination
 15 correction maneuvers by sidereal time/angle ΔS reduces the efficiency of the inclination correction by a factor of $[1-\cos(\Delta S)]$ (here ΔS is considered similar for both maneuvers, although in general cases it may be different for the north and south maneuvers). Nevertheless, in various scenarios during the lifetime of a satellite, the use of such maneuvers may be cost effective (the energy/propellant losses associated therewith may
 20 amount to reasonable energy cost for the eccentricity correction) and it may present an advantageous alternative over other possible eccentricity correction methods. In addition, such maneuvers may be used to extend the lifetime of a satellite in cases where the amount of propellant of other thrusters usable for inclination maneuvers (e.g. north/south thrusters) is low or insufficient.

25 In this regard it should be noted that in some embodiments each of the north and south inclination correction maneuvers extend over an orbital arc preferably not exceeding an angular range of $[-25^\circ, +25^\circ]$ about their respective nominal sidereal angles/times, $Sb^{(N)}$ and $Sb^{(S)}$, to thereby optimize a fuel/energy consumption that is required to adjust both the inclination $\vec{i}$ and the eccentricity $\vec{e}$ by the north and south
 30 maneuvers. To this end, the more powerful the thrusters (e.g. the higher their thrust), the smaller the angular range that needs to be used, and the more efficient the north and south maneuvers of the present invention.

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Thus, in certain implementations of the invention, the north and south inclination correction maneuvers are performed, retarding and advancing the respective nominal sidereal angles/times, $Sb^{(N)}$ and $Sb^{(S)}$ of these maneuvers to compensate over natural (due to solar light pressure) drift of the eccentricity in the negative Y direction and/or changing the ratio R between the thrusts delta-Vs of these maneuvers, $\Delta V^{(N)}$ and $\Delta V^{(S)}$, such that when ratio $R = \Delta V^{(N)} / \Delta V^{(S)} < 1$ is smaller than unity compensation over the natural drift of the eccentricity in the positive inertial X direction is obtained.

Indeed, the techniques exemplified in **Figs. 5A to 5C**, and **Figs. 6A to 6C** may also be combined to provide eccentricity correction in any direction within the X-Y plane. This is exemplified in a self-explanatory manner in **Figs. 7A to 7C**. **Figs. 7A and 7B** which respectively illustrate graphically south and north maneuvers, in which both the magnitude of the thrust delta-Vs, $\Delta V^{(N)}$ and $\Delta V^{(S)}$, and the nominal sidereal angles, $Sb^{(N)}$ and $Sb^{(S)}$, are specifically selected to provide the desired arbitrary inclination and eccentricity corrections, $\Delta \vec{t}^{(tot)}$ and $\Delta \vec{e}^{(tot)}$. The total inclination and eccentricity corrections, affected by the maneuvers of **Figs. 7A and 7B** are illustrated for clarity in **Fig. 7C**. To this end, an eccentricity control method/system according to some embodiments of the present invention may include performing north and south inclination correction maneuvers, by the north and south thrusters respectively, wherein the performing of the north and south maneuvers includes at least one of the following:

- (i) activating the north and the south thrusters with a certain predetermined ratio R of their thrust delta-Vs, $\Delta V^{(N)}$ and $\Delta V^{(S)}$; and (ii) changing the timings, $Sb^{(N)}$ and $Sb^{(S)}$, of those maneuvers with respect to the optimal timing that would be used for inclination corrections only, by predetermined timing variations $\Delta s^{(N)}$ and $\Delta s^{(S)}$, wherein the ratio R and the timing variations $\Delta s^{(N)}$ and $\Delta s^{(S)}$ are selected based on the desired eccentricity correction to adjust the eccentricity in both the x and y directions.

Considering an embodiment of the present invention in which two or more thrusters (indexed j) including at least one north thruster and one south thruster (which are typically, although not necessarily, installed at the north and south panels respectively) with their thrusts $\Delta V^{(j)}$ directed with respective cant angles $\theta^{(j)}$ from the north-south axis, and as such providing the following coupling coefficients C_T and C_R between the components along the north-south axis $\Delta V_{N/S}^{(j)}$ of their thrusts $\Delta V^{(j)}$ and

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their thrust components, $\Delta V_T^{(j)}$ and $\Delta V_R^{(j)}$, in the tangential and in the radial directions:

$$C_T^{(j)} = \frac{\Delta V_T^{(j)}}{\Delta V_{N/S}^{(j)}} \quad \text{and} \quad C_R^{(j)} = \frac{\Delta V_R^{(j)}}{\Delta V_{N/S}^{(j)}}$$

Considering the above thrusters installation, a maneuver carried out by the
5 thruster (j) with given maneuvering parameters: thrust delta-V magnitude $\Delta V^{(j)}$ and timings/sidereal-angle of the maneuver $S_b^{(j)}$, by linearization of the GEO satellite motion equations the effects/corrections $\Delta \vec{t}$ and $\Delta \vec{e}$ of the north/south thrust delta-V at sidereal time/angle $S_b^{(j)}$ on the inclination: $\Delta \vec{t}$ and the eccentricity: $\Delta \vec{e}$, are described by the following relations of Eqs. 1 and 2:

$$10 \quad \text{Eq. (1)} \quad \Delta \vec{t}^{(j)} = \frac{\Delta V_{N/S}^{(j)}}{|\vec{V}^{(j)}|} \begin{pmatrix} \sin(s_b^{(j)}) \\ -\cos(s_b^{(j)}) \end{pmatrix} \quad \text{and}$$

$$\text{Eq. (2)} \quad \Delta \vec{e}^{(j)} = \frac{\Delta V_{N/S}^{(j)}}{|\vec{V}^{(j)}|} \left[2C_T^{(j)} \begin{pmatrix} \cos(s_b^{(j)}) \\ \sin(s_b^{(j)}) \end{pmatrix} + C_R^{(j)} \begin{pmatrix} \sin(s_b^{(j)}) \\ -\cos(s_b^{(j)}) \end{pmatrix} \right]$$

where $|\vec{V}^{(j)}|$ is the satellite's speed at the geostationary orbit, and $|\Delta \vec{V}^{(j)}|$ is the supplemental velocity (namely the thrust delta-V) provided by the (j)th maneuver, $\Delta V_{N/S}^{(j)}$ is the north-south component of the thrust delta-V $\Delta \vec{V}^{(j)}$ along the north south
15 axis (normal to the plane of the orbit) which is given by the projection of the thrust $\Delta \vec{V}^{(j)}$ on the north-south axis as follows $\Delta V_{N/S}^{(j)} = |\Delta \vec{V}^{(j)}| \cos(\theta^{(j)})$, and $\theta^{(j)}$ is the cant angle of the north/south thruster (indexed j) used in the maneuver. In the equations (1) and (2) above it is considered that the thruster(s) provide the main thrust component directed to north-south axis, and also provide a thrust component in the
20 radial and in some cases also in the tangential direction, wherein the ratios between the thrusts in the tangential and radial directions to their thrust, along the north south axis, are given by the coefficients $C_T^{(j)}$ and $C_R^{(j)}$. These can be calculated from the cant angles $\theta^{(j)}$ of the thrusters with respect to the north-south axis while considering their orientations $\varphi^{(j)}$ within the plane spanned by the radial and tangential axes (the plane
25 parallel to the north-south axis) for example as follows:

$$C_T^{(j)} = \tan(\theta^{(j)}) * \sin(\varphi^{(j)}) \quad \text{and} \quad C_R^{(j)} = \tan(\theta^{(j)}) * \cos(\varphi^{(j)}).$$

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Note that the effect of the tangential thrust component on the eccentricity correction is two times stronger than the effect of radial thrust component on the eccentricity as can be demonstrated using the linearized form of the equations of motion in a GEO orbit.

It should be noted that in embodiments of the present invention in which the thrust of the north and/or south maneuvers/thrusters has a substantial tangential component, the tangential component is usable for correcting the eccentricity and also the longitudinal drift of the satellite (in addition to the orbit's inclination correction provided by the north/south component of the thrust). The effects of such tangential component on the eccentricity are expressed above in Eq. (2) (i.e. considering the coupling coefficient C_T). The effects of such tangential component on the longitudinal drift velocity $\vec{L}$ are obtained as follows (where $\Delta\vec{L}$ is the correction of the longitudinal drift velocity)

$$\Delta\dot{L}^{(j)} = -3C_T^{(j)} \frac{\Delta V_{N/S}^{(j)}}{|\vec{V}^{(j)}|} \cdot 361 [^\circ / day]$$

15

Considering equations (1) and (2), the corrections $\Delta\vec{l}^{(tot)}$ and $\Delta\vec{e}^{(tot)}$ obtained by two or more such maneuvers, are as follows:

$$\text{Eq. (3)} \quad \Delta\vec{l}^{(tot)} = \sum_i \Delta\vec{l}^{(i)} \quad \text{and} \quad \Delta\vec{e}^{(tot)} = \sum_i \Delta\vec{e}^{(i)}.$$

Thus, as indicated above, the present invention provides a technique of using the south and/or north thrusters of a satellite for correcting the inclination of the satellite's orbit, its eccentricity, and in some cases also the longitude drift, by performing one or more maneuvers with the north and/or south thrusters of the satellite.

It should be noted that one might contemplate using more than one north and one south thruster to implement control over in-plane parameters (eccentricity and longitudinal drift) of the orbit. For example, using at least four thrusters:

- a North thruster installed with cant angle providing delta-V component in the east direction in addition to the delta-V component in the north direction;
- a north thruster installed with cant angle providing delta-V component in the west direction in addition to the delta-V component in the north direction;

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- a south thruster installed with cant angle providing delta-V component in the east direction in addition to its delta-V component in the south direction;
 - a south thruster installed with cant angle providing delta-V component in the west direction in addition to is the delta-V component in the south direction;
- 5 In such a situation, eccentricity control can, in general, be achieved by selectively operating a selected one of the north thrusters (e.g. the one whose thrust is coupled to the east direction or the one whose thrust is coupled to the west direction) at the optimal timing for the north maneuver, and, accordingly, also selectively operating a selected one of the south thrusters (e.g. a selected one whose thrust is coupled to the east or to
- 10 the west direction) at the optimal time for the south maneuver, while properly distributing the total delta-V necessary for the correction of the inclination between the functioning of the selected north and south thrusters, so as to obtain the desired correction to eccentricity.

However, such implementations may be lacking in some aspects. For one, they

15 require two or more thrusters to be installed with different cant angles (e.g. cant to the west and cant to the east) in each of the north and the south panels. As indicated above, installation of electrical thrusters is generally more cumbersome than installation of chemical propulsion thrusters, and therefore such configuration might be less suitable/less cost effective when use of electrical thrusters is sought. Also, since this

20 technique requires selection of proper thrusters to activate, failure in one of the thrusters may impair the ability to apply proper maneuvers.

To this end, advantageously, the present invention allows to correct the inclination of the satellite orbit by activating only two thrusters, one south maneuver with a north thruster of the satellite, and one north maneuver with a south thruster of the

25 satellite, while enabling to achieve the required eccentricity correction. This can be achieved using only two north and south electrical thrusters installed in the north and the south panels of the satellite, with appropriate cant angles in the radial direction. Also, the technique of the present invention may be used in cases where one of two or more thrusters which were originally installed in the north or south panels, fails. This is

30 achieved, as indicated above, by operating the north thruster/thrusters and the south thruster/thrusters with proper selection of their thrust delta-V's while properly shifting (advancing or retarding, or in other words decreasing or increasing) their operation timings (sidereal angles) with respect to the optimal timing/sidereal angles of the north

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and south maneuvers. As indicated above, the optimal timings for the inclination corrections maneuvers are generally at sidereal angles perpendicular to the desired inclination correction (typically the optimal sidereal angles are near or coincide with the inertial Y axis of the MEGSD coordinate system or at small or moderate angles from the inertial Y axis since the inclination drift is mostly in the inertial X direction).

Therefore, accordingly, in the technique of the invention at least one of the north/south maneuvers is not performed at the optimal sidereal angle, and thus yields eccentricity correction in addition to inclination correction. In other words, as will be described below, the technique of this embodiment of the invention relies on proper advancement and/or retardation of the north and south maneuvers for correcting the inclination and eccentricity, instead of achieving this by selectively using one of two thrusters installed in each of the north and/south panels (which requires at least four thrusters to be installed), while performing the north maneuvers at their optimal timings. The cost is indeed in that the maneuvers, which are not performed at their optimal timings, are somewhat less efficient. However, the inventors of the present invention have found (via calculations and simulations) that the reduction on efficiency resulting from the deviation from the optimal timings is relatively low, and in many cases negligible.

Thus the technique of the present invention advantageously provides for correcting the inclination and the eccentricity by using two, north and south, thrusts to perform two complementary north and south maneuvers (indexed by superscripts (N) and (S)), by operating the two, north and south, thrusters, while obviating a need for using additional thrusters (e.g. obviating a need for additional thrusters in the north/south panels and/or in other panels of the satellite) and also obviating a need for additional maneuvers for this purpose. The north and south maneuvers are performed to accelerate the satellite at corresponding nominal times $\{Sb^{(N)}, Sb^{(S)}\}$ with respective thrust delta-Vs (supplemental velocities) $\{\Delta V^{(N)}, \Delta V^{(S)}\}$, which are directed mainly (although not exclusively) in corresponding north and south directions.

Indeed, it should be understood that according to the invention, correcting the inclination of the orbit as well as both the eccentricity of the orbit and the longitudinal drift of the satellite, are also possible by carrying more than two maneuvers by the north and south thrusters of the satellite, for example, a couple of maneuvers conducted on successive days.

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A general solution to Eq. (1) to (3) above to determine the maneuvers' parameters (thrust delta-Vs $\Delta V^{(j)}$ and sidereal angles $S_b^{(j)}$ achieving desired corrections to the inclination $\vec{\Delta i}$ and the eccentricity $\Delta \vec{e}$ and possibly also for the longitudinal drift velocity $\vec{\Delta L}$ can be obtained via numerical techniques (e.g. numerical simulations). Yet, in the following, exemplified is a specific analytical derivation of the required parameters $\Delta V^{(N)}$, $S_b^{(N)}$, $\Delta V^{(S)}$, $S_b^{(S)}$ for two complementary north and south maneuvers (indexed respectively by superscripts (N) and (S)) which are performed by using the north and south thrusters of the satellite for correcting the inclination $\vec{i}$ and the eccentricity $\vec{e}$. In this example, for which the analytic derivation is provided, the thruster(s) are installed on the satellite such that their thrusts are directed within the plane spanned by the radial axis and north-south axis. Namely the cant angles $\theta^{(j)}$ of the thrusters are therefore measured in this plane which is spanned by the radial axis and north-south axis (i.e. their orientation angles $\phi^{(j)}$ within the plane spanned by the radial and tangential axes are $\phi^{(j)} = 0^\circ$ with respect to the radial axis). Therefore no thrust is provided in this example in the direction tangential to the orbit, and the effects of equations (1) and (2) can be more simply expressed as follows:

$$\text{Eq. (4)} \quad \Delta \vec{i} = \frac{\Delta V_{N/S}}{V} \begin{pmatrix} \sin s_b \\ -\cos s_b \end{pmatrix} ; \quad \Delta \vec{e} = \frac{\Delta V_{radial}}{V} \begin{pmatrix} \sin s_b \\ -\cos s_b \end{pmatrix}$$

wherein S_b is the sidereal angle at the middle of the arc along which the thruster is activated; V is the one-body GEO velocity; $\Delta V_{N/S}$ and ΔV_{Radial} are the thrust delta-V components parallel to the north-south axis and the radial axis respectively; here for a North maneuver $\rightarrow \Delta V_{N/S} > 0$, for a South maneuver $\rightarrow \Delta V_{N/S} < 0$, and $\Delta V_{radial} > 0 \rightarrow$ points to Zenith; the cant angles $\theta^{(N)}$ and $\theta^{(S)}$ of the north and south thrusters are measured from the positive direction of the north-south axis. Thus the radial components of the thrust delta-Vs in the north and south maneuvers may be expressed as follows:

Eq. (5)

$$\begin{aligned} \text{North maneuver} &\rightarrow \Delta V_{radial}^{(N)} = -\sin(\theta_N) \cdot \Delta V^{(N)} \\ \text{South maneuver} &\rightarrow \Delta V_{radial}^{(S)} = \sin(\theta_S) \cdot \Delta V^{(S)} \end{aligned}$$

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where $\Delta V^{(N)}$ and $\Delta V^{(S)}$ are the thrust delta-V of the north and south maneuvers respectively. The north-south components of the thrust delta-Vs in the north and south maneuvers may be expressed as follows:

Eq. (6)

$$\begin{aligned} \text{North maneuver} &\rightarrow \Delta V_{N/S}^{(N)} = \cos(\theta_N) \cdot \Delta V^{(N)} \\ \text{South maneuver} &\rightarrow \Delta V_{N/S}^{(S)} = \cos(\theta_S) \cdot \Delta V^{(S)} \end{aligned}$$

For clarity, in the following, consider the particular case where the north and south thrusters are installed with similar cant angles, namely $\theta^{(N)} = \theta^{(S)} = \theta$. Therefore, based on Eqs. 3 to 6, the total inclination correction and eccentricity correction provided by such two complementary north and south maneuvers may be expressed as follows:

Eq. (7)

$$\begin{aligned} \Delta \vec{i}^{(tot)} &= \Delta \vec{i}^{(N)} + \Delta \vec{i}^{(S)} = \cos(\theta) \left[\frac{\Delta V^{(N)}}{V^{(N)}} \begin{pmatrix} \sin s_b^{(N)} \\ -\cos s_b^{(N)} \end{pmatrix} + \frac{\Delta V^{(S)}}{V^{(S)}} \begin{pmatrix} \sin s_b^{(S)} \\ -\cos s_b^{(S)} \end{pmatrix} \right] \\ \Delta \vec{e}^{(tot)} &= \Delta \vec{e}^{(N)} + \Delta \vec{e}^{(S)} = \sin(\theta) \left[-\frac{\Delta V^{(N)}}{V^{(N)}} \begin{pmatrix} \sin(s_b^{(N)}) \\ -\cos(s_b^{(N)}) \end{pmatrix} + \frac{\Delta V^{(S)}}{V^{(S)}} \begin{pmatrix} \sin(s_b^{(S)}) \\ -\cos(s_b^{(S)}) \end{pmatrix} \right] \end{aligned}$$

These vector equations Eq. (7) are a particular case of equations (1) to (3) above. By inverting the vector equations (7) the following formulas are obtained for determining the thrust delta-Vs ($\Delta V^{(N)}$ and $\Delta V^{(S)}$) and the timings ($Sb^{(N)}$ and $Sb^{(S)}$) parameters for the north and south maneuvers, which will provide the desired inclination Δi and eccentricity Δe corrections:

Eq. (8)

$$\begin{aligned} s_b^{(S)} &= \tan^{-1} \left(-\frac{\Delta i_x \sin(\theta) + \Delta e_x \cos(\theta)}{\Delta i_y \sin(\theta) + \Delta e_y \cos(\theta)} \right); \Delta V^{(S)} = \frac{V^{(S)}}{2 \sin(s_b^{(S)})} \left(\frac{\Delta i_x}{\cos(\theta)} + \frac{\Delta e_x}{\sin(\theta)} \right) \\ s_b^{(N)} &= \tan^{-1} \left(-\frac{\Delta i_x \sin(\theta) - \Delta e_x \cos(\theta)}{\Delta i_y \sin(\theta) - \Delta e_y \cos(\theta)} \right); \Delta V^{(N)} = \frac{V^{(N)}}{2 \sin(s_b^{(N)})} \left(\frac{\Delta i_x}{\cos(\theta)} - \frac{\Delta e_x}{\sin(\theta)} \right) \end{aligned}$$

It should be noted that here $V^{(N)}$ and $V^{(S)}$ are the satellite speeds (orbital velocities) when the north and south maneuvers are respectively performed. However in case of geostationary satellites, such as communication satellites, the orbital velocity,

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generally referred to as V_{GEO} is almost constant (deviating only within a small range of up to $\pm 0.1\%$). Therefore, practically the orbital velocity V_{GEO} can be exchanged in the equation above in place of the velocities $V^{(N)}$ and $V^{(S)}$.

To this end, in some embodiments of the present invention, the required eccentricity and inclination correction, $\Delta \mathbf{e}$ and $\Delta \mathbf{i}$, are selected/provided in operation 5 **210** of method **200** in order to compensate over general/natural trend drifts of those parameters of the orbit, and in order to prevent orbit eccentricity and inclination from exceeding certain prescribed limits associated with the station keeping policy of the satellite. For example, the component Δi_x of the inclination correction may be selected 10 to compensate over the general trend of drift of the inclination i towards the positive x direction. Alternatively or additionally, the component Δi_y of the inclination correction vector $\Delta \mathbf{i}$ may be selected to compensate over long term trends of the inclination of the satellite, to prevent the satellites' inclination from exceeding a certain maximal inclination threshold, and/or it may be selected in accordance with a co-locating policy 15 associated with co-location of the satellite with one or more other satellites. Also, the eccentricity correction components, Δe_x and Δe_y , may be selected based on the station keeping policy, so as to compensate the eccentricity vector drift due to solar pressure, and thus to restrict the longitude daily librations of the satellite to below a certain threshold. Alternatively or additionally, the eccentricity correction components, Δe_x 20 and Δe_y , may also be selected in accordance with a policy requiring co-location of the satellite with one or more other satellites.

Reference is made together to **Figs. 8A to 8C** each exemplifying a pair of north and south daily maneuvers performed by the south and north thrusters. The figures show daily maneuvers performed according to some embodiments of the present 25 invention at different seasons (summer and autumn) in order to cope with natural drift of the orbit inclination and also to cope with the natural drift of eccentricity due to solar pressure. The sun's orientation in these seasons is depicted in the figures and denoted **Sun**. The ΔV lines, $\Delta \mathbf{V}^{(S)}$ and $\Delta \mathbf{V}^{(N)}$, in the figures denote the south and north maneuvers respectively, where their length is proportional to the thrust delta-Vs of 30 these maneuvers and their direction (sidereal angles) point to the sidereal angles $\mathbf{Sb}^{(S)}$ and $\mathbf{Sb}^{(N)}$, at which the maneuvers are performed. The direction and magnitude of the

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required inclination correction (due to typical natural drift of the inclination vector) is also presented and denoted by $\Delta \mathbf{i}$.

Fig. 8A exemplifies a pair of north and south daily maneuvers performed in the summer to correct the eccentricity and compensate the sun's pressure impact on the eccentricity at the solstices, and also to correct the inclination by required correction $\Delta \mathbf{i}$ in the X direction. **Fig. 8B** exemplifies a pair of north and south daily maneuvers performed in the autumn for coping with the sun pressure impact on the eccentricity during this season. To this end, to compensate the effect of the sun pressure on eccentricity, the south maneuver is advanced and the north maneuver is delayed. **Fig.**
10 **8C** exemplifies a pair of north and south daily maneuvers performed in the autumn for coping with the sun pressure impact on the eccentricity and also for compensating the natural drift of the Y component of the inclination. Here, a more general case is presented, in which the inclination correction $\Delta \mathbf{i}$ includes a component in the Y direction. To this end, the required compensation is achieved by setting a proper ratio R
15 between the North and the South $\Delta \mathbf{V}$'s, $\Delta \mathbf{V}^{(N)}$ and $\Delta \mathbf{V}^{(S)}$, and also a proper timing of the middle point of the maneuvers arcs, $\mathbf{Sb}^{(N)}$ and $\mathbf{Sb}^{(S)}$.

Thus the present invention provides methods and systems for the maneuvering of satellites by their south and/or north thrusters to adjust the orbit inclination as well as one or more in-plane orbit parameters, such as orbit eccentricity, and/or longitudinal
20 drift velocity, by exploiting cant angles of the north south thrusters directed to the radial and/or tangential directions. Some non-limiting examples of how the technique of the present invention can be performed are described above. It should be however understood that the present invention is not limited to those specific examples and that those versed in the art will readily appreciate how to implement the invention when the
25 north/south thrusters are installed with different cant angles than those exemplified above, (e.g. where the north/south thrusters provide no-zero thrust component along the tangential direction), and/or how to use the north and/or south thrusters for correcting different combinations of in-plane orbit parameters.

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CLAIMS

1. A method for maneuvering a satellite, the method comprising:
 performing two or more complementary north and south maneuvers to adjust an inclination $\vec{i}$ of an orbit of a satellite, said performing comprising operating north and south thrusters of said satellite, which are respectively installed at panels of the satellite with respective cant angles from the north-south axis, to adjust the inclination $\vec{i}$ of the orbit of the satellite by desired inclination correction $\Delta\vec{i}$; each of said two or more maneuvers, indexed j , generating respective thrust delta-Vs respectively accelerating said satellite by two or more predetermined supplemental velocities $\{\Delta V^{(j)}\}$ at two or more corresponding sidereal angles $\{S_b^{(j)}\}$ along the orbit;
 the method is characterized by shifting at least one of said sidereal angles $\{S_b^{(j)}\}$ of the maneuvers, to increase or decrease it, with respect to the optimal sidereal angle which is perpendicular to the desired overall inclination correction $\Delta\vec{i}$, and thereby adjusting said inclination $\vec{i}$ of the orbit by said desired inclination correction $\Delta\vec{i}$ while also adjusting additional in-plane parameters by desired in-plane corrections including adjusting at least an eccentricity $\vec{e}$ of the orbit by a desired eccentricity correction $\Delta\vec{e}$.
2. The method of claim 1 wherein said satellite is a geostationary satellite and wherein adjustment of said inclination and of in-plane parameters of the orbit including at least said eccentricity $\vec{e}$ of the orbit, are required for station-keeping of said satellite.
3. The method of claims 1 or 2 wherein each of said north and south thrusters is an electrical thruster installed at a cant angle from the north-south providing a thrust vector having a component directed parallel to a north-south axis, and a component directed within the plane of the orbit.
4. The method of claim 3 wherein said in-plane thrust component comprises a component in the radial direction and a component in the tangential direction of said orbit.
5. The method of claim 3 wherein said in-plane thrust component is constituted by a substantial thrust component in the radial direction thereby providing adjustment of the eccentricity $\vec{e}$ of the orbit while having negligible or no effect on in-plane longitudinal parameters of the satellite.
6. The method of any one of claims 1 to 5 wherein said magnitudes of each one of said two or more supplemental velocities $\{\Delta V^{(j)}\}$ and said shifting of the at least one

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sidereal angles $\{S_b^{(j)}\}$, with respect to said optimal sidereal angle, are determined based on said desired inclination corrections $\Delta\vec{i}$ and said desired in-plane corrections in such a way that performing said two or more maneuvers adjust said inclination $\vec{i}$ of the orbit by said desired inclination correction $\Delta\vec{i}$ and additionally adjust said eccentricity $\vec{e}$ by said eccentricity correction $\Delta\vec{e}$.

7. The method of claim 6 wherein said desired in-plane corrections further comprise longitude drift correction $\Delta\vec{L}$ required for correcting the longitudinal drift $\dot{L}$ of said satellite along the orbit and wherein performing said two or more maneuvers adjust said longitudinal drift $\dot{L}$ by said longitude drift correction $\Delta\vec{L}$.

8. The method of any one of claims 1 to 7 comprising providing data indicative of said inclination correction $\Delta\vec{i}$ and said in-plane corrections, and said data is used to determine said two or more supplemental velocities $\{\Delta V^{(j)}\}$ and said two or more corresponding nominal angles $\{S_b^{(j)}\}$.

9. The method of claim 8 wherein said two or more supplemental velocities $\{\Delta V^{(j)}\}$ and said two or more corresponding nominal angles $\{S_b^{(j)}\}$ are determined by the inverse form of the following relations:

$$\Delta\vec{i} = \sum_j \left[\frac{\Delta V_{N/S}^{(j)}}{|\vec{V}^{(j)}|} \begin{pmatrix} \sin(s_b^{(j)}) \\ -\cos(s_b^{(j)}) \end{pmatrix} \right]$$

$$\Delta\vec{e} = \sum_j \left[\frac{\Delta V_{N/S}^{(j)}}{|\vec{V}^{(j)}|} \left[2C_T^{(j)} \begin{pmatrix} \cos(s_b^{(j)}) \\ \sin(s_b^{(j)}) \end{pmatrix} + C_R^{(j)} \begin{pmatrix} \sin(s_b^{(j)}) \\ -\cos(s_b^{(j)}) \end{pmatrix} \right] \right]$$

wherein $V^{(j)}$ is the satellite speed tangential to the orbit at the time of maneuver (j), and $\Delta V_{N/S}^{(j)}$ is the magnitude of the north-south components of the thrust delta-V provided by the (j) maneuver and $C_T^{(j)}$ and $C_R^{(j)}$ are coupling coefficients associated with the magnitudes of the tangential and radial components of the thrust delta-V, respectively.

10. The method according to any one of the preceding claims wherein said two or more maneuvers comprise two complementary north and south inclination correction maneuvers respectively performed by operating said north and south thrusters of the satellite at respective nominal sidereal angles $\{S_b^{(N)}, S_b^{(S)}\}$ to accelerate said satellite

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by North and South supplemental velocities $\{\Delta V^{(N)}, \Delta V^{(S)}\}$ which are mainly directed in corresponding north and south directions.

11. The method according to claim 10 wherein the time at which the north inclination correction maneuver is performed, corresponds to the satellite's location $Sb^{(N)}$ within an arc of the orbit in the angular range of $[-30^\circ, +30^\circ]$ about the negative direction of the inertial Y axis, and the time at which the south inclination correction maneuver is performed, corresponds to the satellite's location $Sb^{(S)}$ within an arc of the orbit in the angular range of $[-30^\circ, +30^\circ]$ about the positive direction of said inertial Y axis.

12. The method of claim 10 or 11 comprising adjusting a ratio R between said north and south supplemental velocities $\{\Delta V^{(N)}, \Delta V^{(S)}\}$, to thereby provide desired correction Δe_x to the eccentricity of the satellite's orbit along the inertial X axis e_x .

13. The method according to any one of claims 10 to 12 comprising decreasing or increasing at least one of said sidereal angles $\{Sb^{(N)}, Sb^{(S)}\}$, at which the north and south inclination correction maneuvers are performed with respect to the optimal sidereal angle to thereby provide desired correction Δe_y to the eccentricity of the satellite's orbit along the inertial Y axis.

14. The method according to any one of claims 10 to 13 wherein said north and south thrusters are installed at the same cant angles θ from the north-south axis such that their thrusts include a thrust component parallel to the north-south axis and a thrust component in the plane of the orbit directed substantially exclusively in the radial direction; the method comprising determining the supplemental velocities $\{\Delta V^{(N)}, \Delta V^{(S)}\}$ and the corresponding sidereal angles $\{Sb^{(N)}, Sb^{(S)}\}$ of the north and south maneuvers based on said desired inclination and eccentricity corrections, $\Delta \vec{i}$ and $\Delta \vec{e}$ utilizing the following relations:

$$s_b^{(S)} = \tan^{-1} \left(-\frac{\Delta i_x \sin(\theta) + \Delta e_x \cos(\theta)}{\Delta i_y \sin(\theta) + \Delta e_y \cos(\theta)} \right); \Delta V^{(S)} = \frac{V_{GEO}}{2 \sin(S_b^{(S)})} \left(\frac{\Delta i_x}{\cos(\theta)} + \frac{\Delta e_x}{\sin(\theta)} \right)$$

$$s_b^{(N)} = \tan^{-1} \left(-\frac{\Delta i_x \sin(\theta) - \Delta e_x \cos(\theta)}{\Delta i_y \sin(\theta) - \Delta e_y \cos(\theta)} \right); \Delta V^{(N)} = \frac{V_{GEO}}{2 \sin(S_b^{(N)})} \left(\frac{\Delta i_x}{\cos(\theta)} - \frac{\Delta e_x}{\sin(\theta)} \right)$$

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where V_{GEO} is the orbital velocity of said satellite, Δi_x and Δi_y are the vector components of the desired inclination correction $\Delta \vec{i} \equiv [\Delta i_x, \Delta i_y]$, and $\Delta e_x, \Delta e_y$ are the vector components of the desired eccentricity correction $\Delta \vec{e} \equiv [\Delta e_x, \Delta e_y]$.

15 **15.** The method according to any one of claims 1 to 14 comprising at least one of the following:

- (a) determining a value of at least one of the X and Y components $\Delta i_x, \Delta i_y$ of the inclination required correction vector $\Delta \vec{i}$ in accordance with at least one of a station keeping and a co-location policy of the satellite so as to compensate over the general trend of drift of the inclination $\vec{i}$ of the orbit;
- 10 (b) determining a value of at least one of the X and Y components $\Delta e_x, \Delta e_y$ of the eccentricity required correction vector $\Delta \vec{e}$ in accordance with at least one of a station keeping and a co-location policy of the satellite such that said eccentricity correction vector $\Delta \vec{e}$ provides at least partial compensation for the natural drift of the eccentricity $\vec{e}$;
- 15 (c) determining a value of Δe in accordance with a station keeping policy of the satellite so as to restrict longitude daily librations of said satellite to below a certain predetermined threshold.

20 **16.** The method of any one of claims 1 to 15 wherein said at least one of the north and south thrusters of the satellite having a predetermined respective thrust and wherein the method comprises:

- utilizing data indicative of said respective thrust value to determine two or more sidereal arcs $\{\Delta S_b^{(j)}\}$ along the orbit corresponding to said two or more maneuvers and at which said at least one of the north and south thrusters should be operated to execute a respective maneuver (j); and
- 25 - operating said at least one of a north and south thrusters along said two or more sidereal arcs $\{\Delta S_b^{(j)}\}$ to thereby effectively accelerate said satellite by said predetermined respective supplemental velocities $\{\Delta V^{(j)}\}$ at said nominal sidereal angles $\{S_b^{(j)}\}$.

30 **17.** The method according to claim 16 wherein said nominal sidereal angles $\{S_b(j)\}$ are at the middle of their respective sidereal arcs $\{\Delta S_b(j)\}$; and wherein

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lengths of said sidereal arcs $\{\Delta S_b(j)\}$ are determined in accordance with respective supplemental velocities $\{\Delta V(j)\}$ to be supplemented to satellite velocity during a corresponding (j) maneuver, a thrust force provided by a respective one of the north and south thrusters used in the corresponding (j) maneuver, the mass of said satellite, and
 5 the date on which the orbital correction is executed, being associated with the direction of eccentricity drift caused by solar radiation pressure.

18. A computer readable device storing computer readable code for carrying out the method of claim 1.

19. A control system for maneuvering a satellite, comprising:

10 a maneuvering controller configured and operable for determining maneuvering data indicative of two or more complementary north and south maneuvers, indexed j, to be performed by north and south thrusters of a satellite arranged with cant angle(s) with respect to a north-south axis;

said maneuvering controller is configured and operable for

15 determining thrust delta-Vs $\{\Delta V^{(j)}\}$ indicative of respective accelerations of said satellite during said two or more complementary maneuvers and corresponding sidereal angles $\{S_b^{(j)}\}$ along the orbit, at which to respectively perform said two or more complementary maneuvers, in order to obtain desired orbit corrections including desired inclination correction $\Delta \vec{i}$ for adjusting an inclination $\vec{i}$ of an orbit of said
 20 satellite, and at least one correction of an in-plane parameter of the orbit which includes at least a desired eccentricity correction $\Delta \vec{e}$ for adjusting an eccentricity $\vec{e}$ of the orbit;

wherein said maneuvering processor is adapted to adjust said at least one in-plane parameter of the orbit in addition to adjustment of the inclination of the orbit by shifting at least one sidereal angle $S_b^{(j)}$ of said sidereal angles $\{S_b^{(j)}\}$ of the maneuvers
 25 relative to an optimal sidereal angle, which is perpendicular to the desired inclination correction $\Delta \vec{i}$, such that said at least one sidereal angle $S_b^{(j)}$ is increased or decreased with respect to the optimal sidereal angle to thereby provide for adjusting at least said eccentricity $\vec{e}$ of the orbit by said desired eccentricity correction $\Delta \vec{e}$ in addition to said adjustment of the inclination $\vec{i}$.

30 **20.** The control system of claim 19 comprising an orbit correction data provider configured and operable for providing said maneuvering processor with orbit correction

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data including data indicative of said inclination and eccentricity corrections, $\Delta \vec{i}$ and $\Delta \vec{e}$, required for station-keeping of said satellite in a geostationary orbit.

21. The control system of claim 19 or 20 wherein said north and/or south thrusters are electrical thrusters installed with said cant angles from the north-south axis in such a way that they provide a thrust vector having a component directed parallel to a north-south axis, and a component directed within the plane of the orbit and including at least a radial thrust component.

22. The control system of any one of claims 19 to 21 configured and operable for determining said thrust delta-Vs $\{\Delta V^{(j)}\}$ and said sidereal angles $\{S_b^{(j)}\}$ of the two or more complementary maneuvers to further adjust a longitudinal drift $\dot{L}$ of said satellite along the orbit by desired longitude drift correction $\Delta \dot{L}$.

23. The control system of any one of claims 19 to 22 wherein the maneuvering processor is adapted to determine said two or more supplemental velocities $\{\Delta V^{(j)}\}$ and said two or more corresponding nominal times $\{S_b^{(j)}\}$ by utilizing the following relations:

$$\Delta \vec{i} = \sum_j \left[\frac{\Delta V_{N/S}^{(j)}}{|\vec{V}^{(j)}|} \begin{pmatrix} \sin(s_b^{(j)}) \\ -\cos(s_b^{(j)}) \end{pmatrix} \right]$$

$$\Delta \vec{e} = \sum_j \left[\frac{\Delta V_{N/S}^{(j)}}{|\vec{V}^{(j)}|} \left[2C_T^{(j)} \begin{pmatrix} \cos(s_b^{(j)}) \\ \sin(s_b^{(j)}) \end{pmatrix} + C_R^{(j)} \begin{pmatrix} \sin(s_b^{(j)}) \\ -\cos(s_b^{(j)}) \end{pmatrix} \right] \right]$$

wherein $V^{(j)}$ is the satellite speed tangential to the orbit at the time of maneuver (j), and $\Delta V_{N/S}^{(j)}$ is the magnitude of the north-south components of the thrust delta-V provided by the (j) maneuver and $C_T^{(j)}$ and $C_R^{(j)}$ are coupling coefficients associated with the magnitudes of the tangential and radial components of the thrust delta-V, respectively.

24. The control system of any one claims of 19 to 23 comprising a thruster controller module adapted to operate said north and/or south thrusters of the satellite in accordance with said maneuvering data to perform said two or more complementary maneuvers and thereby adjust said inclination and eccentricity of said satellite.

25. The control system of any one claims 19 to 24 wherein said two or more maneuvers determined by said maneuvering processor are constituted by two

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complementary north and south maneuvers respectively performed by operating said north and south thrusters of the satellite at respective nominal sidereal angles $\{S_b^{(N)}, S_b^{(S)}\}$ to accelerate said satellite by north and south supplemental velocities $\{\Delta V^{(N)}, \Delta V^{(S)}\}$.

5 **26.** The control system of claim 25 wherein the maneuvering processor is adapted to set the time at which the north inclination correction maneuver is performed to correspond to the satellite's location $S_b^{(N)}$ within an arc of the orbit in the angular range of $[-30^\circ, +30^\circ]$ about the negative direction of the inertial Y axis, and set the time at which the south inclination correction maneuver is performed to correspond to the
10 satellite's location $S_b^{(S)}$ within an arc of the orbit in the angular range of $[-30^\circ, +30^\circ]$ about the positive direction of said inertial Y axis.

27. The control system of claims 25 or 26 wherein said maneuvering processor is adapted to set a ratio R between the thrust delta-Vs $\{\Delta V^{(N)}, \Delta V^{(S)}\}$ of said north and south maneuvers in such a way that a desired correction Δe_x to the eccentricity e_x of the
15 orbit along the inertial X axis is obtained.

28. The control system of any one of claims 25 to 27 wherein said maneuvering processor is adapted to decrease or increase at least one of said sidereal angles $\{S_b^{(N)}, S_b^{(S)}\}$, of said north and south maneuvers with respect to the inertial Y axis such that a desired correction Δe_y to the eccentricity e_y of the satellite's orbit along the inertial
20 Y axis is obtained.

29. The control system of any one of claims 25 to 28 wherein said maneuvering processor is adapted to determine the thrust delta-Vs $\{\Delta V^{(N)}, \Delta V^{(S)}\}$ and the corresponding sidereal angles $\{S_b^{(N)}, S_b^{(S)}\}$ of the north and south maneuvers based on utilizing the following relations:

$$25 \quad s_b^{(S)} = \tan^{-1} \left(-\frac{\Delta i_x \sin(\theta) + \Delta e_x \cos(\theta)}{\Delta i_y \sin(\theta) + \Delta e_y \cos(\theta)} \right); \Delta V^{(S)} = \frac{V_{GEO}}{2 \sin(S_b^{(S)})} \left(\frac{\Delta i_x}{\cos(\theta)} + \frac{\Delta e_x}{\sin(\theta)} \right)$$

$$s_b^{(N)} = \tan^{-1} \left(-\frac{\Delta i_x \sin(\theta) - \Delta e_x \cos(\theta)}{\Delta i_y \sin(\theta) - \Delta e_y \cos(\theta)} \right); \Delta V^{(N)} = \frac{V_{GEO}}{2 \sin(S_b^{(N)})} \left(\frac{\Delta i_x}{\cos(\theta)} - \frac{\Delta e_x}{\sin(\theta)} \right)$$

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where V_{GEO} is the orbital velocity of said satellite, Δi_x and Δi_y are the vector components of the desired inclination correction $\Delta \vec{i} \equiv [\Delta i_x, \Delta i_y]$, and $\Delta e_x, \Delta e_y$ are the vector components of the desired eccentricity correction $\Delta \vec{e} \equiv [\Delta e_x, \Delta e_y]$.

30. The control system of any one of claims 19 to 29 wherein said maneuvering
 5 processor is adapted to utilize data indicative of said respective thrust values of said
 north and south thrusts to respectively determine two or more sidereal arcs $\{\Delta S_b^{(j)}\}$
 along the orbit corresponding to said two or more maneuvers at which said at least one
 of the north and south thrusters should be operated to execute said respective
 maneuvers.

10

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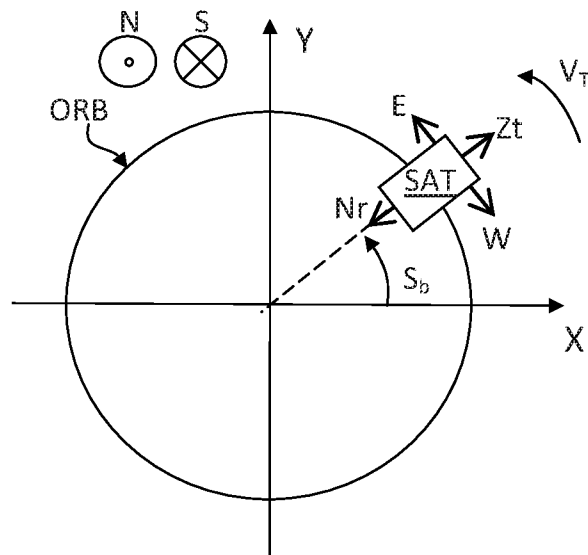


Fig. 1A (General Art)

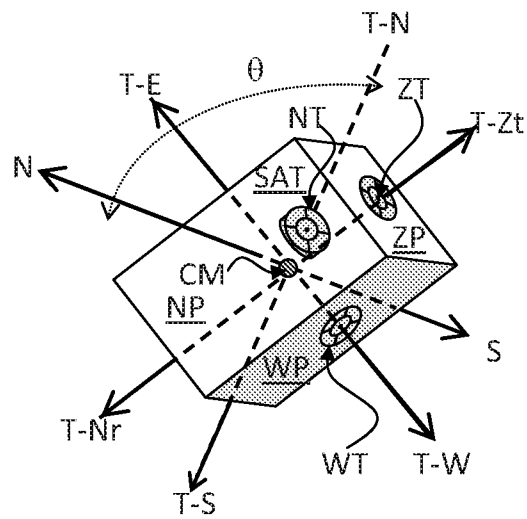
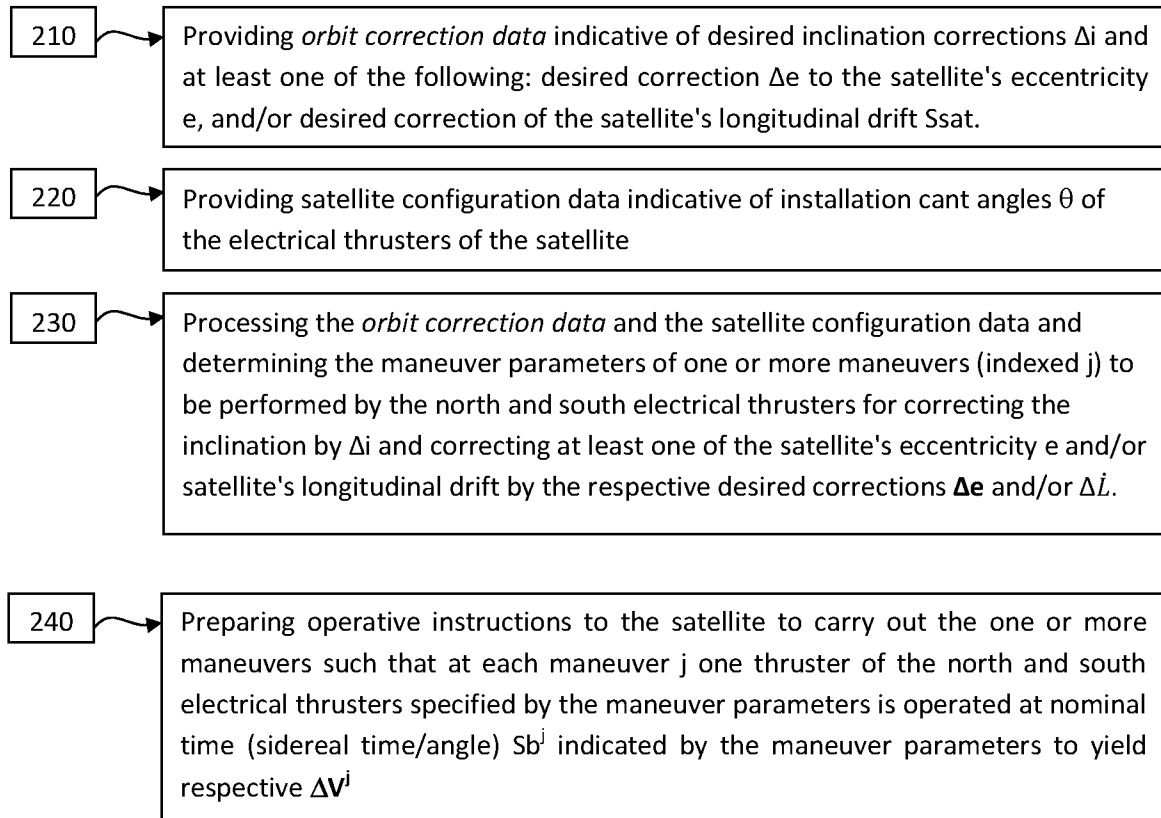


Fig. 1B (General Art)

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200**Fig. 2A**

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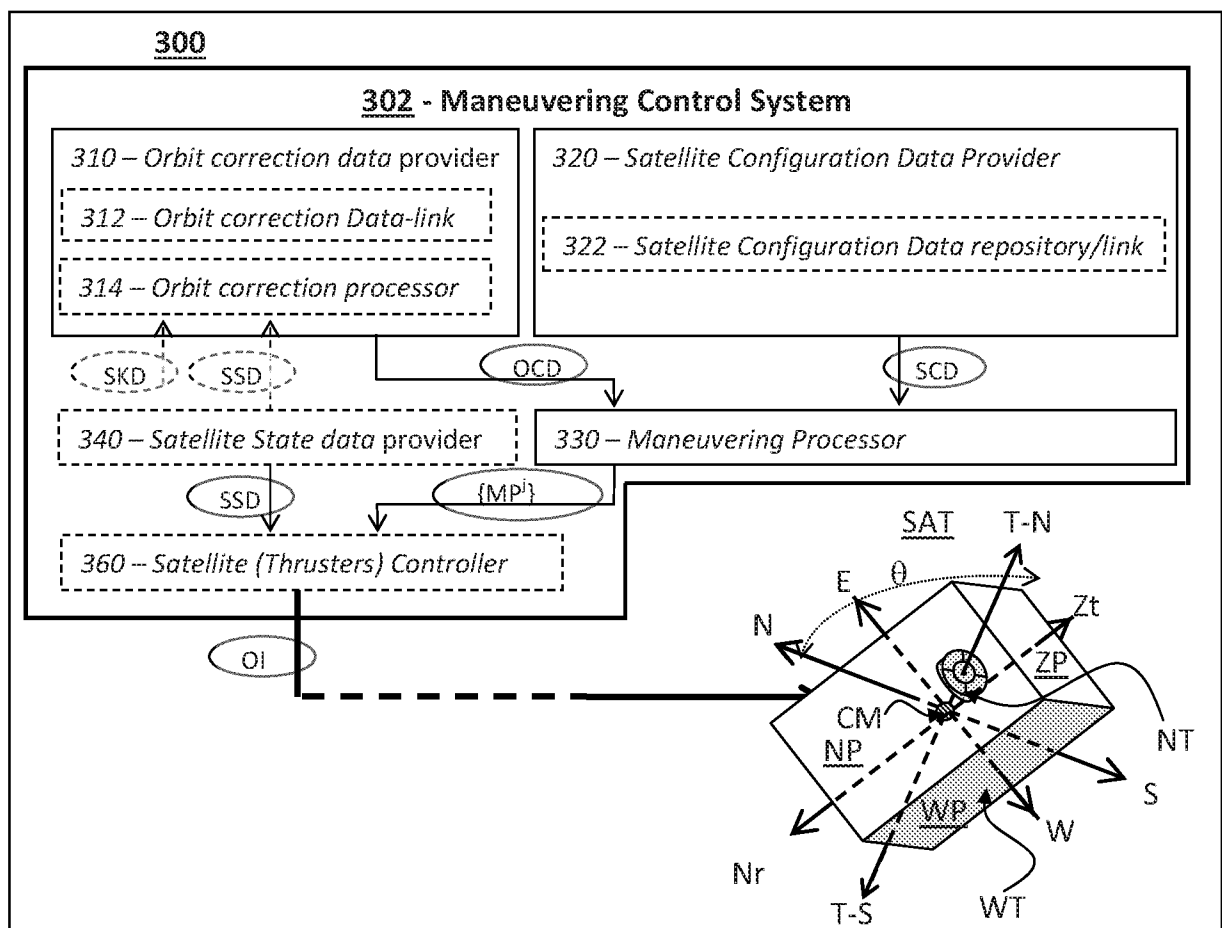


Fig. 2B

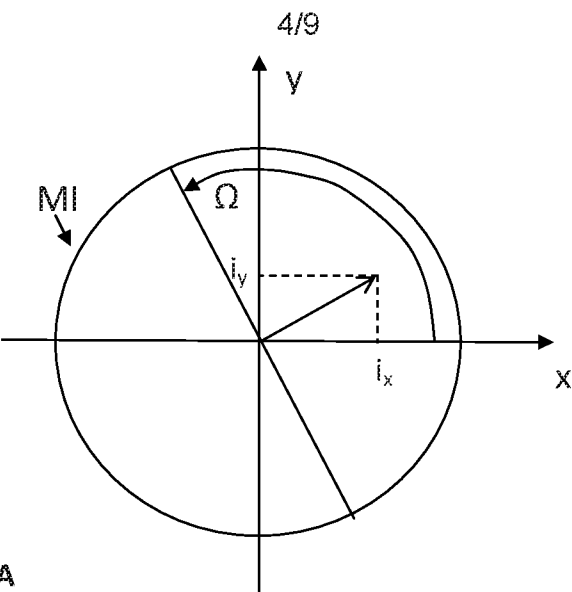


Fig. 3A

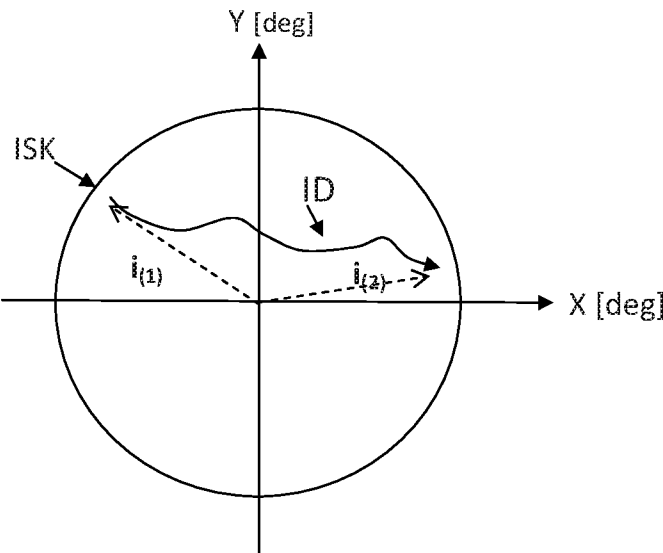


Fig. 3B

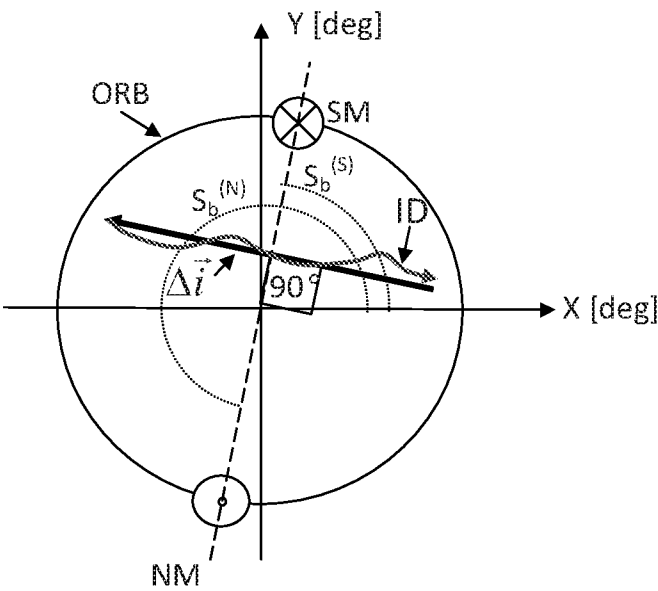


Fig. 3C

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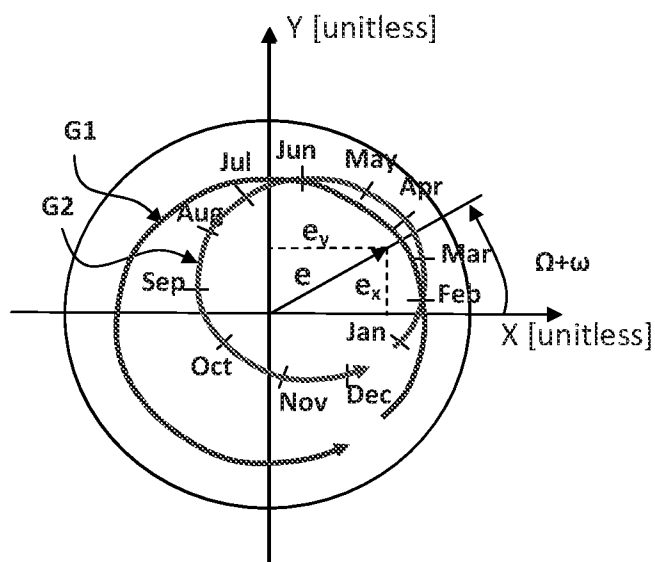


Fig. 3D

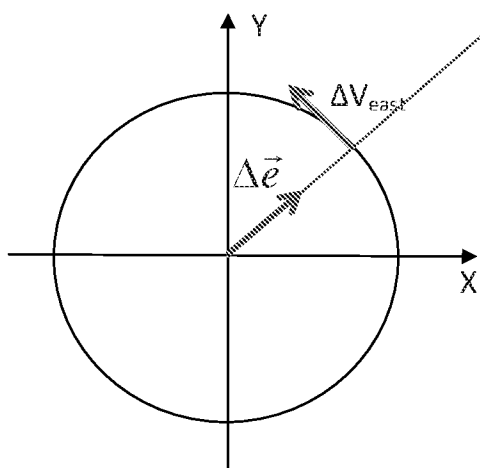


Fig. 3E

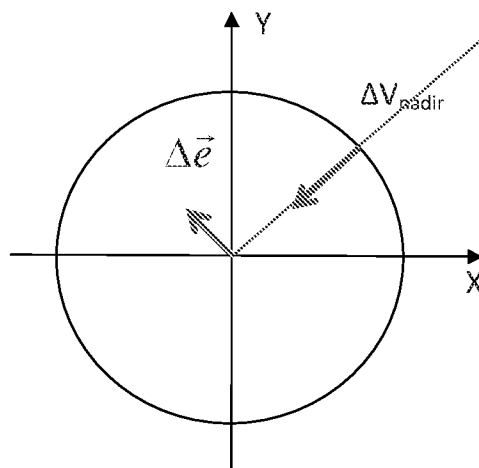


Fig. 3F

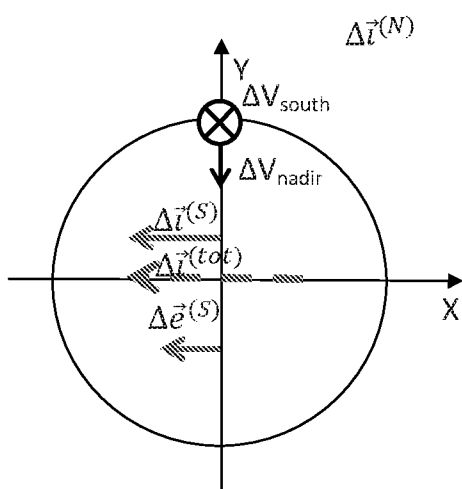


Fig. 4A (General Art)

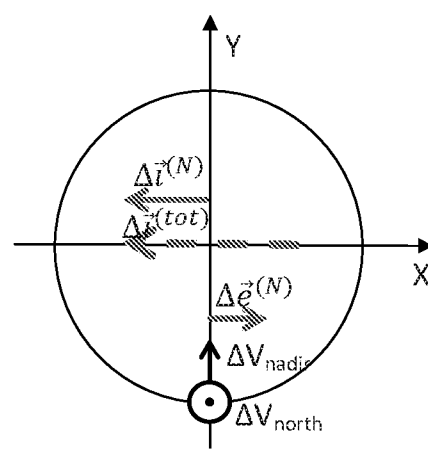
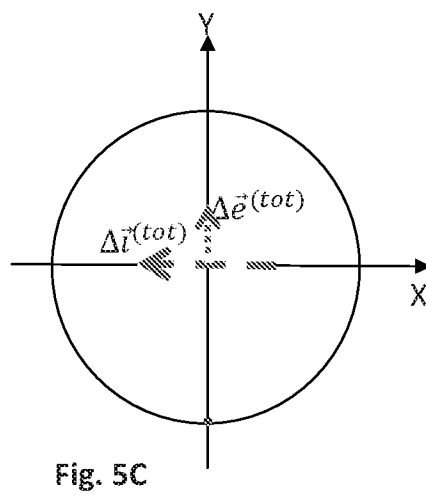
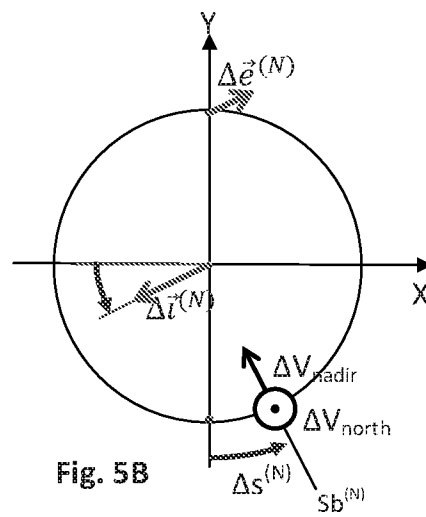
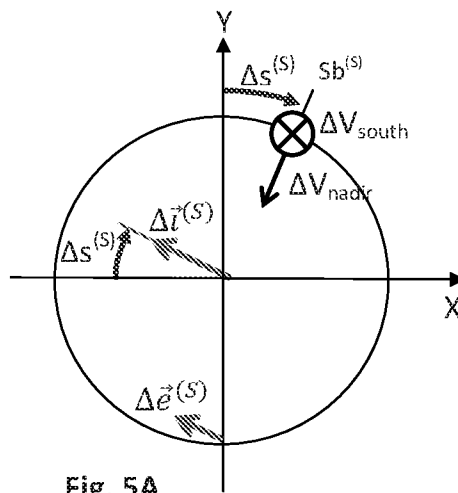
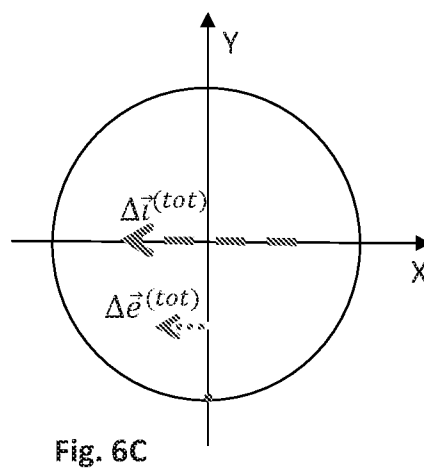
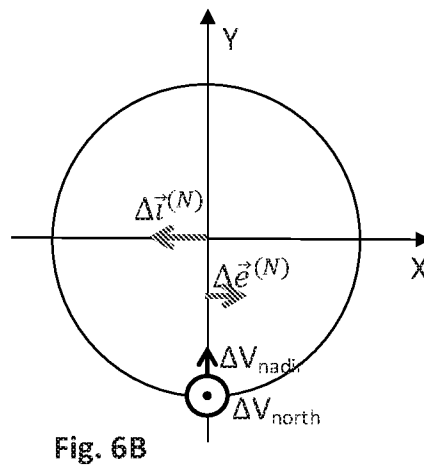
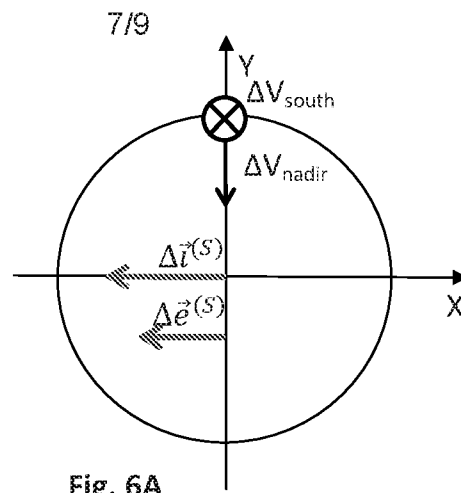


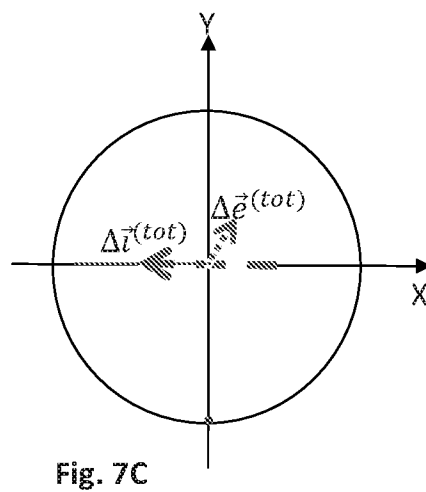
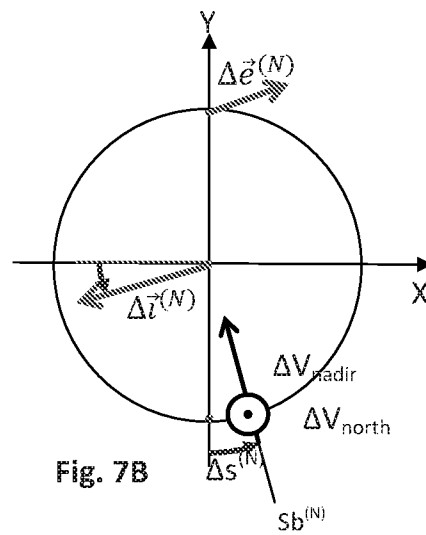
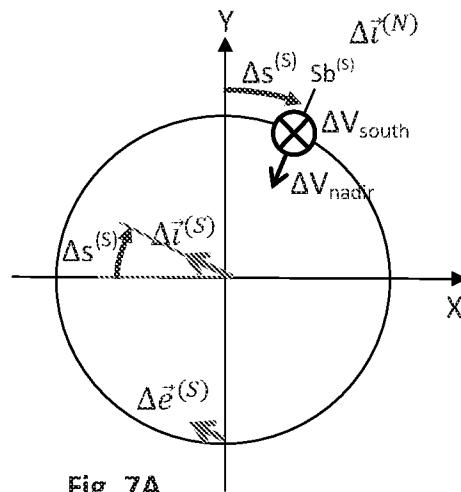
Fig. 4B (General Art)

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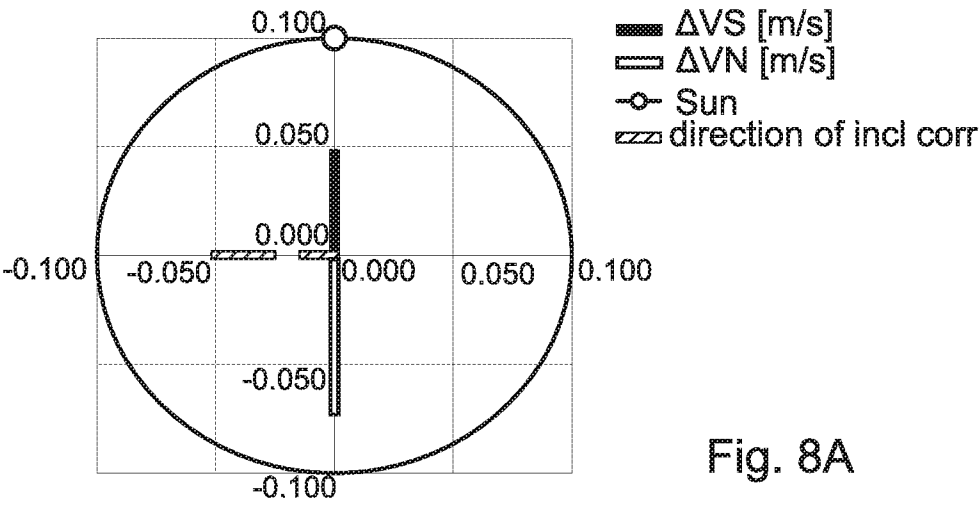


Fig. 8A

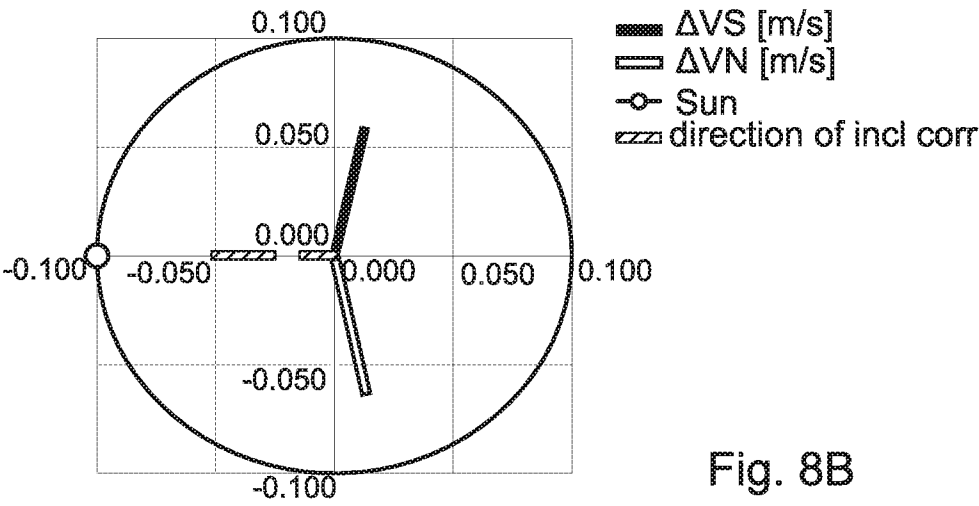


Fig. 8B

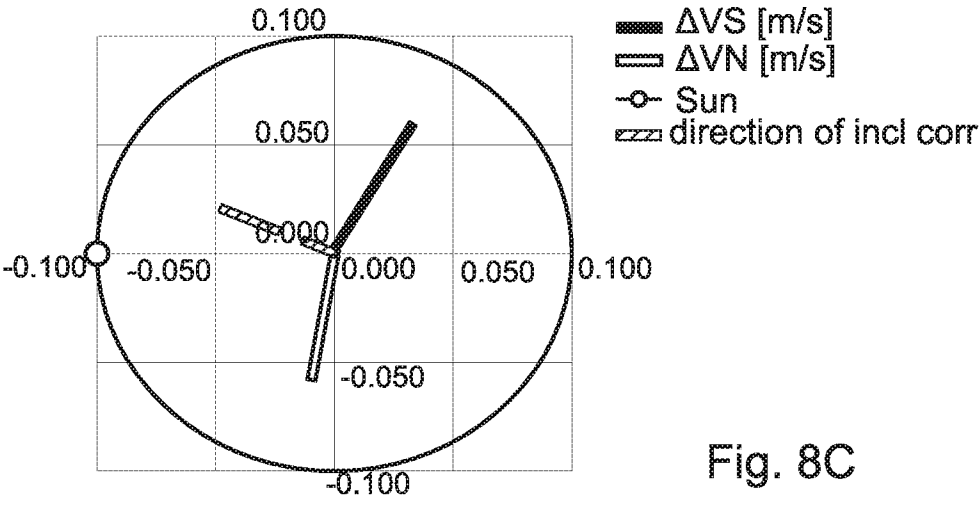


Fig. 8C

INTERNATIONAL SEARCH REPORT

International application No

PCT/IL2016/050104

A. CLASSIFICATION OF SUBJECT MATTER

INV. B64G1/24 B64G1/26
 ADD. B64G1/40

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
 B64G

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6 135 394 A (KAMEL AHMED A [US] ET AL) 24 October 2000 (2000-10-24) column 1, lines 4-9 column 2, line 55 - column 4, line 63 column 5, line 52 - column 6, line 3 figures	1-8, 10-13, 15-22, 24-28,30
A	----- EP 0 818 721 A1 (HUGHES AIRCRAFT CO [US]) 14 January 1998 (1998-01-14) the whole document	1-30
A	----- EP 0 654 403 A1 (HUGHES AIRCRAFT CO [US]) 24 May 1995 (1995-05-24) the whole document ----- -/-	1-30



Further documents are listed in the continuation of Box C.



See patent family annex.

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Date of the actual completion of the international search

20 May 2016

Date of mailing of the international search report

31/05/2016

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Weber, Carlos

INTERNATIONAL SEARCH REPORT

International application No

PCT/IL2016/050104

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
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Information on patent family members

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