Small satellites constellations for continuous regional surveillance

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SMALL SATELLITES CONSTELLATIONS FOR CONTINUOUS REGIONAL SURVEILLANCE

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Abstract

The present considerable interest in low Earth light-weight satellite constellations for remote sensing missions has lead to satellite systems providing continuous coverage of particular areas.

The paper describes a technique for obtaining efficient revisit coverages and repeat cycles from satellites distributed on one or more orbital planes.

Two constellations deployed on Sun-Synchronous and Multi-Sun-Synchronous planes have been chosen to take into account perturbative environmental effects and subsequent required station keeping considerations.

1. Introduction

There is a considerable interest, today, in low-Earth, light-weight satellite constellations for various missions including communication, navigation and surveillance. Some of this interest is directed at constellations that provide non-continuous temporal coverage of particular areas, rather than continuous regional or global coverage. Early detection of hazard and time effective disaster monitoring is a growing problem, especially for certain areas in the world. The ability to detect and monitor environmental disasters, by limiting at the largest possible extent their effects, is one of the most important target in applications of remote sensing for the near future. The most critical parameter to be taken into account is the time for intervention, depending on detection, isolation and, whenever possible, recovery capability. Currently, remote sensing satellites orbiting the Earth and collecting a large amount of data, are able to cover global aspects of environmental monitoring but they do not meet the detail and the repetitivity of observation required in a disaster management, able to provide products characterized by fast delivery from acquisition, optimum source selection and integration of acquired data in a territorial database. The characterizing features (e.g. area of interest, spatial characteristics, evolution and control time) drive the system design of detection and monitoring from space. When comparing these characteristics with the performance of current remote sensing missions, it is evident that several requirements are not satisfied; in fact these satellites, located in sun-synchronous orbits, are useful to study the temporal and spatial evolution of phenomena characterized by relatively slow variations over several days, weeks or months. If faster response times are needed, as in the case of natural disasters, standard remote sensing satellites are not able to provide the timely and updated information required: aircraft and/or ground based reconnaissance are often used instead. The detection of contingencies is possible only if a sufficient number of sensors is available, then the constellation appears the only solution in order to limit the temporal gaps of acquisition caused by the utilization of a single spacecraft. In fact, the only space sensors which satisfy sampling rate of less than 12 hours are the geostationary radiometers, generally used for the monitoring of hurricanes and weather condition. A single satellite in geostationary orbit might provide in principle the necessary coverage, but to be really helpful it should carry on board very sophisticated high resolution sensors. Moreover, the launch cost of high altitude spacecraft is prohibitive and even the demise of a single one would need a costly replacement to maintain the system capabilities. Presently, contingencies (e. g. floods, earthquakes, forest fires) which require a high sampling rate and a high resolution do not match with any available space borne sensor. A sampling rate of 6 hrs and a ground resolution of 100-200 meters are expected to meet most requirements for environmental management. On the other hand, an efficient ground infrastructure, connecting the regional operation center with the space related facilities, is necessary to create an efficient integrated system.

The paper first details how to produce the orbital characteristics to perform the total number of ground traces necessary to guarantee a complete spatial coverage of the target area with an efficient revisit frequency. Two constellations located in orbital sunsynchronous (SS) and multi-sun-synchronous (MSS) planes are proposed for detection and monitoring of natural disaster; the approach taken is limited to circular orbits and a station keeping analysis has been carried out.

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2. Single Satellite Repeating Ground Tracks Pattern

The possibility to observe the same area with a repetitivity of m nodal days is given by the relation:

$$mD_n = RT_n \tag{1}$$

where T_n is the orbital nodal period, D_n is the nodal day, R is the total number of revolutions performed in the desired repetition cycle m; the satellite will produce a continuous ground track pattern and the consequent westward longitudinal separation between successive equatorial crossing (S_t) is given as:

$$S_t = T_n(\omega_E - \Omega') \tag{2}$$

where ω_E is the angular Earth rotation and Ω' is the orbital nodal ratio. The difference in longitude of two equatorial crossings within S_t with the same direction of travel is given by:

$$\lambda_d = \lambda_0 + S_t \mathrm{mod}(dQ) \tag{3}$$

where d is the number of nodal days elapsed from the starting time d=0, Q is the fractional part of the number of orbits performed in one day, $Q=k/m$ and

$$\mathrm{mod}(x) = frac(x) - int\left[frac(x) + \frac{1}{2}\right] \tag{4}$$

is the operator which allows to have the subsequent nodal crossing within $\pm S_t/2$. k is a prime integer with m which defines the ground track spacing, whereas the equally co-rotating ground tracks spacing at the end of the repeat cycle m results as: $S_m = S_t/m$. The choice of a uniformly distributed ground tracks at the end of the repeat interval depends on the desired S_m ($S_m \leq$ swath width of the instrument). If Q < 1/2 then the pattern will move eastward, whereas if Q>1/2 the pattern will move from east to west. Each day the satellite will cross the equator twice (ascending and descending nodes) within this longitude band S_t. If Q=0 then the number of orbits performed must be an integer and the repeat interval m is only one day. At the conclusion of the repeat interval, the ground track pattern will be completed; the R ascending and R descending crossings will be distributed along the equator. Hopkins (Ref. 1) demonstrated that the angular separation between adjacent ascending and descending crossing can only be one of the two possible value: 0 or π/R. In the latter case all equatorial crossings will be uniformly distributed with respect to each other; then the closest non zero separation at the conclusion of the repeat interval is $S_t/2m$ instead of S_t/m. This minimum value can be accomplished between consecutive co-rotating and counter-rotating equatorial crossings on a given day if m and R are suitably selected. Indicating with N_i the integer part of the repetition factor (number of orbits performed in one nodal days) we can say that this happens when k=1 (N_i odd) or k=m-1 (N_i even); both requirements are fully compatible for uniform distribution and assure the steady eastward or westward progression respectively. For a non equatorial ground track pattern the longitudinal difference at latitude φ on day d between co-rotating and counter-rotating crossings is:

$$\overline{\Delta\lambda}_\varphi = \bar{\lambda}_{d\varphi} - \lambda_\varphi = S_t \mathrm{mod}\left(d\frac{k}{m} + \bar{f} - 2sf_\varphi\right) \tag{5}$$

and

$$\lambda_\varphi = \lambda_0 + S_t s' f_\varphi \tag{6}$$

where s and s' are the integer parameters equal to ± 1 in accordance with the direction of satellite motion, s corresponding to the co-rotating (+1) or counter-rotating (-1) crossing and s' corresponding to a northbound (+1) or a southbound (-1) satellite,

$$\bar{f} = \frac{k}{2m} - \frac{1}{2} \quad (N_i\ even)$$
$$\bar{f} = \frac{k}{2m} \quad (N_i\ odd) \tag{7}$$

and

$$f_\varphi = \frac{\alpha}{S_t} - \frac{\Delta M}{2\pi} \tag{8}$$

represents the fractional shift in longitude due to a non equatorial crossing (see Fig. 1). Unlike co-rotating crossing (where the longitudinal difference at the equator remains invariant with latitude), the longitudinal difference between ascending and descending crossings will vary with latitude. At some latitudes these crossings will be widely separated, while at other latitudes they will intersect. The earth central angular separation at latitude φ between a counter rotating crossing $\lambda_{d\varphi}$ and the reference crossing λ_φ is equal to:

$$\Delta\theta = \overline{\Delta\lambda}_\varphi \cos\varphi \tag{9}$$

In the case of equatorial crossings, it was shown that at the conclusion of the repeat intervals, the ascending and descending nodes were either coincident or uniformly distributed. This is no longer the case at non-equatorial latitudes. While the longitudinal separation between crossings of the same type remains constant (S_t/m), the minimum separation, S_φ, between ascending and descending crossings at the conclusion of the repeat interval, depends on the value of f_φ:

$$S_\varphi = \frac{S_t}{m}\mathrm{mod}\left[m(3 + \bar{f} - 2sf_\varphi)\right] \tag{10}$$

Condition for coincidence:

$$0 = \mathrm{mod}\left[m(3 + \bar{f} - 2sf_\varphi)\right] \tag{11}$$

Condition for uniformly distributed ground tracks at latitude φ becomes:

$$\frac{1}{2} = \mathrm{mod}\left[m(3 + \bar{f} - 2sf_\varphi)\right] \tag{12}$$

At the equator f_φ=0.

Since f_φ varies with latitudes, the two relations can be used to find either the values of latitude at which ascending and descending ground tracks will coincident or those latitude values which present an uniform distribution at the conclusion of the repeat cycle. Depending on the orbital inclination, *i*, the complete coverage of the area of interest is accomplished if

$$S_\varphi \sin i \le \textit{swath width of the instrument} \tag{13}$$

3. Design of constellation for an efficient repeating coverage

The previous considerations showed that a single satellite is able to yield coverage of the area for a few number of consecutive revolutions, creating a significant gap in coverage between them. This gap, less than the orbital period, can be covered either in a low repetition cycle by a large swath of the instrument (then, at scarce ground resolution) or with a scarce temporal resolution if a better detail of observation is required. The best solution is obtained when the gap (either temporal or spatial) is reduced by using a satellite constellation which can consist of satellites deployed on one or more orbital planes. This solution, in fact, has the potential of significantly improving the frequency of observation or the possibility of reducing the minimum spacing between ground tracks at the same repetition cycle. However, if a revisit frequency lower than 12 hours is desired, the solution always requires more than 1 orbital plane. In a constellation design the optimum solution is influenced by characteristics of the payload and observation requirements; these parameters also influence the number of additional satellites and their distribution along one or more orbital planes. If a single plane is chosen and N is the number of satellites of the constellation, and m the single satellite repeat cycle, the relative inter-orbit phasing between two satellites is given by:

$$\frac{\Delta M}{2\pi} = \frac{I-1}{Nm^*} \tag{14}$$

with I = 1, 2,...N and m* an integer number with $1 \le m^* \le m$ which defines the type of distribution of the N satellites along the orbit. m* = 1 represents an evenly spaced distribution whereas m*>1 (asymmetrical distribution) does not guarantee equally spaced nodal crossings at the end of the repeat cycle, except for m*=m for which a repeat cycle of the single satellite (m days) is maintained and a separation as S_t/Nm results. If at time t_0 the ground track of satellite 1 crosses the equator at a longitude $\lambda_{1,0}$ then the co-rotating equatorial crossing within $S_t/2$ of λ_0 by satellite I on day d occurs at longitude:

$$\lambda_{I,d} = \lambda_{1,0} + S_t \bmod\left[d\frac{k}{m} + \frac{I-1}{N}\right] \tag{15}$$

Hereinafter we will consider only equally spaced satellites; in this case the possibilities are as follows:

r = repeat cycle (nodal days)	ground tracks spacing	m/r = number of surveys in m days
(lcm)/N	S_t/(lcm)	mN/(lcm)

with lcm=*Least Common Multiple between N and m.*

The addition of one or more orbital planes to a constellation has the potential of furtherly improving both revisit and spatial coverage; in fact a technique can be derived for deploying satellites in a constellation either to reduce the minimum spacing between adjacent ground tracks or to maximize number of surveys over the repeat interval of a single satellite. A constellation of P planes, with N satellites equally deployed on each plane, is considered; if $\Delta\Omega$ is the relative nodal separation and ΔM the relative inter-orbit phasing between two satellites of two different orbital planes, the first co-rotating equatorial crossing within $S_t/2$ of the longitude of nodal crossing of satellite 1 of the first plane results:

$$\lambda_{p,I,d} = \lambda_{1,1,0} + S_t \bmod\left\{d\frac{k}{m} + \frac{I-1}{N} + \left[\frac{\Delta M}{360} + \frac{\Delta\Omega}{S_t}\right]_p\right\} \tag{16}$$

with p = 2, ..., P. If the patterns are superimposed properly, the minimum grid spacing at the end of the repeat interval would be reduced to S_t/(P•lcm) representing uniform spacing at the equator, keeping the same observation frequency of a constellation deployed in a single plane. The condition for uniformly distributed ground tracks results:

$$\frac{1}{NP} = frac\left[2m\left(\frac{\Delta M}{360} + \frac{\Delta\Omega}{S_t}\right)_p\right] \tag{17}$$

The grid will be composed by ground tracks crossing the equator at different local hours (even for SS orbits). A worst case of superimposition would produce coincident pattern (no reduction in spacing) but higher revisit frequency (at different local time) on the same trace. The number of surveys in m days will be P•m/r and the condition for coincidence is given by:

$$0 = frac\left[2m\left(\frac{\Delta M}{360} + \frac{\Delta\Omega}{S_t}\right)_p\right] \tag{18}$$

Since the nodal separation depends usually on the desired revisit frequency, in the same day, the relative inter-orbit phasing could be adjusted to further improve the ground track pattern.

3. Orbit selection

Among the requirements of a remote sensing system the orbit periodicity (repetitivity) and the same geometry of solar illumination for optical system operating in the reflected part of the electromagnetic spectrum assume significant importance in the mission design. The last requirement occurs when the difference between the apparent solar motion Ω_s', where (') indicates the derivative with respect to the time, and Ω' is submultiple of the difference between the angular Earth rotation ω_E and Ω'. This can be expressed by the relation involving the orbital characteristics, semimajor axis a and inclination i, and n, number of *nodal days* necessary to reencounter the same geometry of illumination:

$$\Omega' = \frac{n\Omega_s' \mp \omega_E}{n \mp 1} \tag{19}$$

The upper sign is valid for $\Omega' < \Omega_s'$, the lower one corresponds to $\Omega' > \Omega_s'$. Eq. (19) is represented in Fig. 2 for different values of the number of nodal days n; it is evident that if $n \to \infty$ the sunsynchronous condition occurs. The multi-sunsynchronous condition is obtained by solving simultaneously the equations (1) and (19) for the semimajor axis a and imposing that m is a submultiple of n. Whereas (19) gives infinity solutions for a (and the corresponding orbit inclination) the periodicity constraint (1), once defined m and R, allows a limited discrete number of solutions according to the following equation obtained combining equations (1) and (19):

$$a^2 + C_1 a^{0.5} + C_2 = 0 \tag{20}$$

with

$$C_1 = -\frac{\sqrt{\mu}}{2\pi}\cdot\frac{m}{R}\cdot\frac{n \mp 1}{n}$$
$$C_2 = -\frac{K}{\mu}\cdot\frac{\pi}{180}(4\cos^2 i - 1) \tag{21}$$

being μ the Earth's gravitation parameter, $K = 1.5 J_2 R_E^2 \sqrt{\mu}$ and i the orbit inclination. Examples of solution are shown in /2/, /3/ and /4/. Multi-sun-synchronous orbits, recently proposed by the authors, are characterized by high revisit frequency, submultiple of the same condition of illumination geometry. Satellites located in these low Earth orbits (both prograde and retrograde) could use less demanding sensors and could be launched at an accessible cost.

4. Constellation configuration maintenance

The perturbations affecting the motion of each satellite of the constellation have different effects on the evolution of the orbit parameters, depending on orbit selection. From the point of view of the constellation geometry maintenance the key parameters to be examined are a, e (eccentricity), i, $\Delta\Omega$, ΔM_{do} (different orbital plane phasing) and ΔM_{so} (single orbital plane phasing). Assuming that all satellites are characterized by the same surface, mass and orientation it results that satellites located on the same orbital plane undergone an equal semi-major-axis reduction and equal inclination and right ascension drifts. This statement is supported by a large number of simulations; then, if the constellation consists of some satellites deployed on the same orbital plane, the problem of the station keeping requirements in terms of fuel budget reduces to an evaluation of the time interval between two consecutive maneuvers, necessary to compensate the eastern ground track drift (consequence of the atmospheric drag effect) in order to keep it within the required longitudinal slot. The effect of differential perturbations on $\Delta\Omega$ and ΔM_{do} are of principal concern when we are considering constellations with satellites located on more than one orbital plane. Other perturbations than drag have a negligible effect on phasing, whereas the effect of all the perturbations on the inter-nodal distance $\Delta\Omega$ can be considered negligible. In general, the phasing change due to the drag force is a consequence of the dependence of the atmospheric density by the satellite local time, and for a SS satellite by the nodal local time. This differential semi-major axis reduction leads to a different increase of the mean motion n and then a variation of the nominal value of ΔM_{do}. This corresponds to a selective drift of nominal ground track pattern for satellites deployed on different orbital planes. This relative drift can be computed, assuming for the diurnal density variation a Fourier fourth order series as follows (ref. 5):

$$\rho(t) = \rho_0 + \sum_{i=1}^{4} A_i \cos(\omega_i \tau - \varphi_i) \tag{22}$$

where ρ_0 represents the diurnal mean value of the density at a certain altitude (the latitude density dependance has been neglected), A_i, ω_i and φ_i are, respectively, amplitude, frequency and phase of the ith harmonic and τ is the hour local time. The evolution of the mean anomaly, taking into account the effect of the drag on the orbit semi-major-axis and then on the mean motion can be written as follows:

$$M(t) = M_0 + n_0(t - t_0) - \frac{3}{4}\frac{n_0}{a_{mean}}\frac{da}{dt}\Big|_{mean}(t - t_0)^2 \tag{23}$$

where M_0 and n_0 are the mean anomaly and the mean motion respectively of the generical satellite at $t=t_0$ and da/dt_{mean} is given by:

$$\frac{da}{dt}\Big|_{mean} = \frac{B}{t - t_0}\int_{t_0}^{t} \rho(\tau)\,d\tau \tag{24}$$

where B has the expression:

$$B = -\sqrt{\mu\, a_{mean}}\, B^* \tag{25}$$

with B* the satellite ballistic coefficient.
The inter-orbit phasing variation can be computed by using the following relationship:

$$\Delta M_{do} = -\frac{3}{4}\left[\left(\frac{da}{dt}\right)_{2,mean} - \left(\frac{da}{dt}\right)_{1,mean}\right](t - t_0)^2 \tag{26}$$

The size of this variation is strongly dependent on the orbit characteristics of the constellation. It always results higher for a SS orbit constellation with respect to a MSS one, due to the characteristics of the diurnal density variation. Assuming two satellites on different orbital planes with $\Delta\Omega = 90$ [deg] and nodes at 12:00 and 18:00 hours local time respectively, we found for the MSS case $\Delta M_{do} \approx 0$ in the limit of the assumption of negligible latitude effect on the density, whereas the following value resulted for the SS case:

$$\Delta M_{do} = 3\frac{\mu}{a^2_{mean}} B^* A_2 \cos\varphi_2 (t - t_0) \qquad (27)$$

In this particular circumstance the inter-phasing drift is due mainly to the second harmonic of the diurnal density variation. The amplitude of the second harmonic is about the 20% of the mean value of the density at the altitude of interest; then, the inter-phasing variation is about the 20% of the orbital mean anomaly variation due to the drag effect. Simulations performed by GEODYNE II package confirm qualitatively these conclusions; then, the relative control results to be more fuel demanding for a SS constellation than for a MSS one. This appears to be further true if we consider the different ballistic coefficient that satellites can exhibit on different orbital planes, due to the different orientation of the solar arrays always faced the sun. There are some circumstances where an absolute control of the constellation could be unnecessary; in any case a relative control of the constellation geometry is required, in order to guarantee the superposition of the ground track patterns. The only relative control corresponds to extend the time interval between to consecutive orbit maneuvers; in this case, in fact, the same ground tracks performed initially by the satellites of a single plane will be re-encountered but the pattern will be performed by different satellites. Then, the absolute maneuver correction could be carried out only when the altitude decay does not allow longer total ground coverage.

5. Numerical application

In order to perform some numerical evaluation we considered an SS orbit with characteristics given in TAB. 1 corresponding to a repeat cycle $m = 5$ and a MSS orbit with the initial parameters given in TAB. 1 corresponding to $m = 5$ and $n = 60$, nodal days. Ground track patterns on the Mediterranean area are represented in figs. 3 and 4 for a SS and MSS satellite respectively. Five satellites deployed on the same orbital plane allow to reduce the repeat cycle to 1 nodal day. Two orbital planes with $\Delta\Omega=$ 90 [deg] are taken into account in order to reduce the repeat cycle to 12 hours if only the ascending or descending part of the orbit is useful for the observation or to 6 hours if active microwave instruments are embarked. The ballistic coefficient assumed ($B^* = 0.007$ [m^2/Kg]) is the same for each satellite of the constellation. The satellites on the same orbital plane results evenly spaced 72° apart each other in mean anomaly; then, the minimum distance between two adjacent co-rotating crossings results $S_m = 463$ [km] at a mean latitude of 30 deg. (Mediterranean area). The inter-orbit phasing of a satellite on the second orbital plane has been chosen in order to halve the repetition cycle. After 120 nodal days, numerical simulations give a ground traces shift of about 220 km, due to the atmospheric drag effect (fig. 5). If we assume that ±5 km is the largest allowed shift of the ground traces, the time interval between two consecutive maneuvers, depending on the solar and geomagnetic activity, would be about 25 days and, taking into account the number of satellites of the constellation, this requirement could be hard demanding in terms of ground control center activity. However, the possibility of not operating the absolute control of any satellite, until the swath width of the instrument is no longer able to guarantee a complete coverage of the target area, could be considered. In order to guarantee a reduction of the repetition cycle, the relative control cannot be delayed. If the limit of ±5 km is hold, the correction of the semi-major axis of the satellites on the SS plane, where the drag effect is larger, will become necessary after 74 days. No relative correction is necessary for a MSS constellation. A numerical propagation of 120 days, for the orbits with initial parameters shown in TAB. 1, gave:

$$\begin{aligned} \Delta M &\cong 0 \quad [deg] \qquad MSS\ case \\ \Delta M &= 3.6\ [deg] \qquad SS\ case \end{aligned} \qquad (28)$$

Fig. 6 shows the different semi-major axis reduction for two satellites of the constellations. In order to monitor a mid latitude region a MSS constellation seems to be preferable with respect to a SS one because less demanding in terms of relative correction as well as capable of covering the target area for a longer period. In fact, the total contact times with a mid latitude ground station (Scanzano, Sicily) are:

$$MSS\ T_c = 416.6 \quad [\text{min}/day]$$

$$SS\ T_c = 295.1 \quad [\text{min}/day]$$

6. Conclusions

The paper has described a technique for obtaining efficient revisit coverages and repeat cycles from multi-satellites constellations deployed on different orbital planes. This technique results in equally spaced satellite ground tracks at different latitudes at the end of the repeat interval. Two constellations deployed on SS and MSS planes have been chosen to take into account perturbative environmental effects and subsequent required station keeping considerations. MSS constellations have resulted less demanding in terms of fuel consumption and more efficient in terms of visibility with a mid latitude ground station.

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TAB. 1

MSS initial orbit parameters	SS initial orbit parameters
a = 7006.38 [km]	a = 7007.45 [km]
e = 0.0007461 (frozen)	e = 0.00105446 (frozen)
i = 44.49 [deg]	i = 97.904 [deg]
Ω= 0 and 90 [deg]	Ω= 0 and 90 [deg]
ω= 90 [deg]	ω = 90 [deg]
M = 0 [deg]	M = 0 [deg]

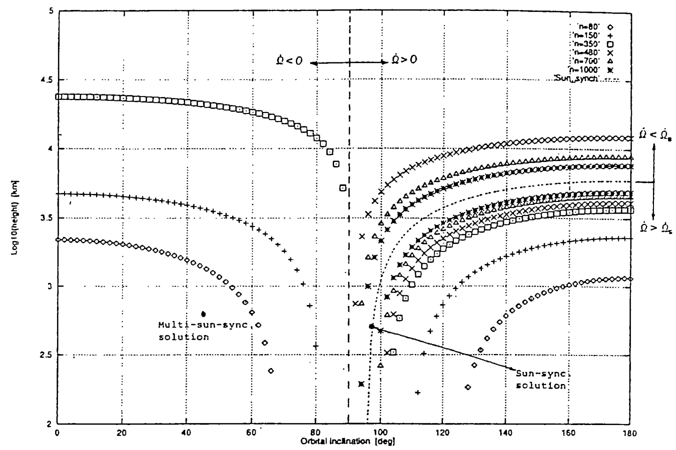

Fig. 2 - Possible solutions of Eq. (19). The dashed line corresponds to sunsynchronous conditions.

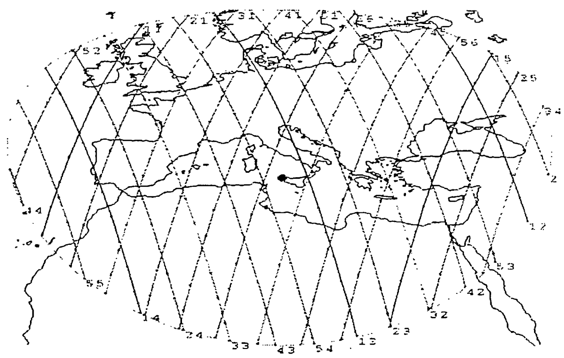

Fig. 3 - Ground track pattern on the Mediterranean area, SS satellite.

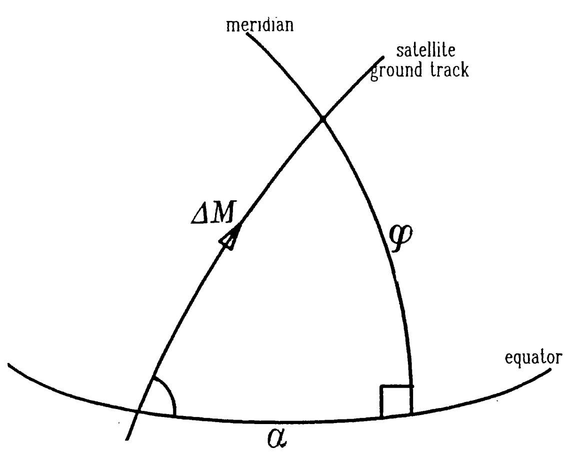

Fig. 1 - Geometry of Eq. (8).

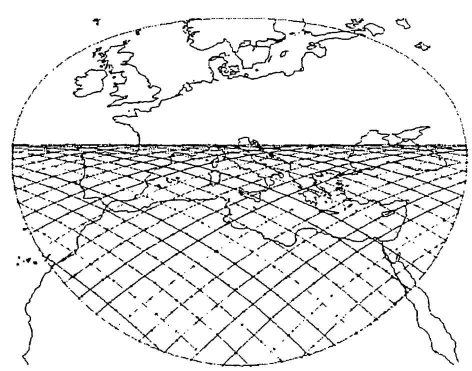

Fig. 4 - Ground track pattern on the Mediterranean area, MSS satellite

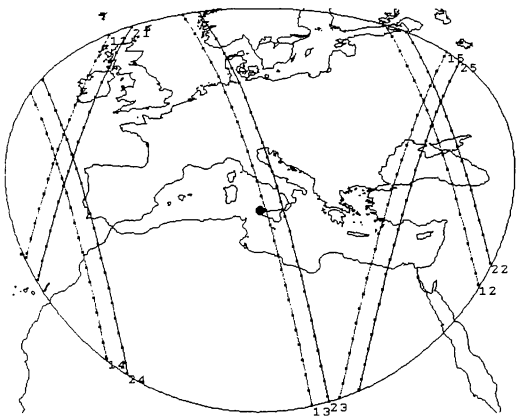

Fig. 5 - SS ground tracks drift due to the drag effect after 120 nodal days.

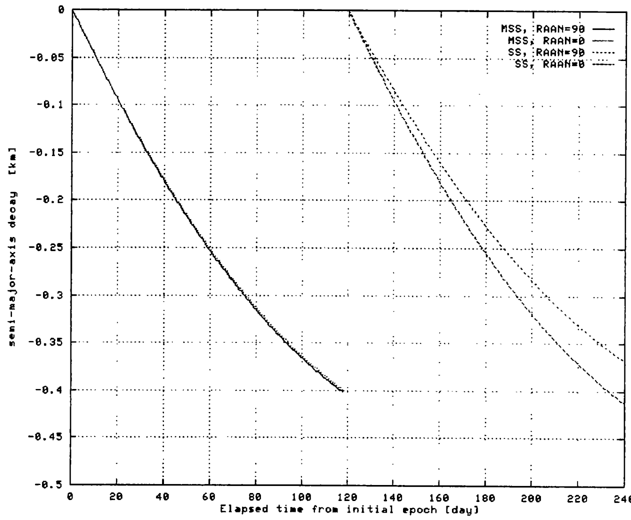

Fig. 6 - Differential drag effect on MSS and SS satellites with a differen orbital node.