4.2 ORBIT DESIGN ANALYSIS FOR REMOTE SENSING SATELLITE CONSTELLATIONS

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Abstract

Earth observing systems are evaluated by performance parameters including area coverage and observation repetitivity; the type of mission is in fact determined by the area to be covered (global or regional) and by whether the repetitivity requirement calls for continuous or intermittent observations.

The majority of published technical papers deal with continuous global coverage for applications in telecommunication. Some works in remote sensing missions developed algorithms to minimize maximum revisit time or to evaluate by geometrical approaches the average access time to a certain target.

This paper, following early works on single satellite mission analysis for intermittent coverage, concentrates on manipulation of the ground track patterns of satellite constellations. The task, then, is to describe an orbit design analysis oriented to obtain efficient revisit coverages and repeat cycles by instruments embarked on satellite constellations deployed on one or more orbital planes.

If the patterns are superimposed properly, it is possible either to reduce the minimum grid spacing (related to the swath width of the onboard instrument) or to increase the revisit frequency on the same trace.

The analysis is limited to the study of constellations consisting of satellites located on circular orbits with the same altitude and inclination.

Results are depicted, by considering an orbit analysis for observation of the Mediterranean area.

Introduction

The survey areas accessible to a sensor mounted in a satellite, as it travels around the earth, depend on the instrument field of view and on orbital parameters as altitude and inclination which determine the the satellite trace over the surface of the earth.

The orbit to be used in any particular remote sensing mission has always been determined through a trade-off between coverage objectives and the capabilities of the sequential trace pattern development, taking also into account the desired ground resolution.

Coverage missions usually fall into two general categories:

i) complete intermittent survey of a given area during a relatively short period;

ii) continuous surveillance of a target area.

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

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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 of the single satellite.

However, if a revisit frequency lower than 24 hours is desired, the solution always requires more than one 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 (Ref. 1).

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.

The paper, following early works on single satellite mission analysis for intermittent coverage, describes an orbit design analysis oriented to obtain efficient revisit coverages and repeat cycles by instruments embarked on satellite constellations deployed on one or more orbital planes.

If the patterns are superimposed properly, it is possible either to reduce the minimum grid spacing (related to the swath width of the onboard instrument) or to increase the revisit frequency on the same trace.

The analysis is limited to the study of constellations consisting of satellites located on circular orbits with the same altitude and inclination (uniform constellations).

Results are depicted, by considering an orbit analysis for observation of the Mediterranean area.

Single plane constellations

A single satellite of the constellation will produce a continuous ground track pattern able to yield coverage of the area of interest for a few number of consecutive revolutions, causing a significant spatial gap between them, decreasing with latitude.

The westward longitudinal separation between successive equatorial crossing (S_t) is given as:

$$S_t = T_n(\omega_E - \Omega') \qquad (1)$$

where ω_E is the angular Earth rotation, Ω' is the orbital nodal ratio and T_n is the orbital nodal period, related to the nodal day D_n by the periodicity condition

$$mD_n = RT_n \qquad (2)$$

where m is the repetitivity of observation (in nodal days) for the same ground trace and R is the total number of revolutions of the satellite occurred in the desired repetition cycle m.

For sun-synchronous orbits the nodal day coincides with the solar one.

The number of orbits performed in one day is R/m and can be split in two terms according to the relation

$$\frac{R}{m} = N_i + N_f = N_i + \frac{k}{m} \qquad (3)$$

where N_i is the integer number of orbits performed daily and N_f (named "repetition factor") is its fractional part; k, prime integer with m and $1 \le k \le m-1$, defines the ground tracks spacing.

After m days, the longitudinal increment S_t will be divided in m equal increments of longitude $S_m = S_t/m$; during the pattern development between two consecutive nodes, each day's nodal co-rotating crossing occurs east (or west) of the previous day's node by $\pm kS_m$ where the sign is positive or negative if $k<m/2$ or $k>m/2$ respectively.

S_m is related to the swath width of the instruments and influences the choice of a uniformly distributed ground tracks at the end of the repeat interval. In fact coverage of the earth's equatorial region from a satellite is accomplished if the swath width on the earth's surface required for coverage is equal to the minimum longitudinal interval S_m between earth traces. If $N_f=0$ then the number of orbits performed must be an integer and the repeat interval m is only one day.

If a single plane ($P=1$) is considered and N is the number of satellites of the constellation, the ground track of satellite I crosses the equator on day d at a longitude

$$\lambda_{I,d} = \lambda_{1,0} + S_t \mathrm{mod}\left[d\frac{k}{m} + \frac{\Delta M}{2\pi}\right] \qquad (4)$$

where $\lambda_{1,0}$ is the co-rotating crossing longitude of the satellite 1 at the time t_0 ($d=0$) and ΔM is the relative inter-orbit phasing between two satellites. The operator

$$\mathrm{mod}(x) = frac(x) - int\left[frac(x) + \frac{1}{2}\right] \qquad (5)$$

allows to have subsequent crossings within $\lambda_{1,0} \pm S_t/2$, according to the Hopkins's notation (Ref. 2).

If d days is the interval between two observations over the same trace, it will result $\lambda_{I,d} = \lambda_{I,0}$ and the argument of the operator *mod* will be an integer; then $(dk/m) + (\Delta M/2\pi) = d$ that leads to the generical solution:

$$\Delta M = 2\pi d\left(\frac{m-k}{m}\right) = 2\pi d(1 - N_f)$$

$$or \qquad (6)$$

$$360 \cdot d(m-k) = m\Delta M$$

N surveys will result for the entire coverage with a minimum grid spacing corresponding to that one of a single satellite of the constellation (S_t/m), whereas the revisit frequency is still m days. A typical example is given by the two ESA polar orbiting satellites: ERS-1 and ERS-2. The two spacecraft are controlled to fly along the same orbit with ERS-2 following ERS-1 at a ΔM such that its Synthetic Aperture Radar (SAR) can image exactly the same areas imaged 24 hours before by the SAR of ERS-1, allowing the acquisition of good SAR image pairs for interferometric applications, almost all over the world (Ref. 3). According to Eq. (6) the two instruments inter-orbit phasing value results ($d=1$ *day*, $k=11$, $m=35$ *days*)

$$\Delta M = 360\,(35-11)/35 = 246.86 \quad degrees.$$

In order to have a daily repetitivity for the entire coverage, N must be equal to m; i.e. evenly deployed satellites (homogeneous constellation).

Limiting our interest to homogeneous constellations, the choice of the number of satellites on the same orbital plane will be a trade-off between the necessity of having a complete coverage with the observing instrument (*swath width of the instrument* $\geq S_m \sin i$, with i the orbital inclination) at a suitable repetitivity depending on the time scale of the observed event and the other constellation requirements.

If it is necessary to improve the repetitivity in the trace performed by a single satellite, a daily observation could be obtained and S_m would result the same as for a single satellite ($S_m = S_t/m$), whereas N would result the maximum number of surveys performed in m nodal days for the target area.

If the scope were to reduce the minimum spacing between adjacent ground tracks, the repeat cycle r could be maintained as lcm/N nodal days whereas S_m could be reduced to $S_m = S_t/lcm$ with lcm = Least Common Multiple between N and m. Then, the number of surveys m/r allowed would result mN/lcm.

Multi-plane constellations

The addition of one or more orbital planes to a constellation has the potential of further 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. Both requirements need to have the same number of ground traces performed in the common repeat interval, i.e. the same lcm for the same P couple of values m, N. In fact, even though with the same lcm, different values of m, N for different planes would cause a drifting distribution of the ground traces due to the different value of the repetition factor N_f. If a constellation of P planes, with N satellites equally deployed on each plane, is considered, and $\Delta\Omega$ and ΔM_p are respectively the relative nodal separation and the relative inter-orbit phasing between two satellites of two different orbital planes, the first co-rotating equatorial crossing within $\pm S/2$ of the longitude of nodal crossing of satellite *1* of the first plane results:

$$\lambda_{p,I,d} = \lambda_{1,1,0} + S_t \bmod\left\{ d\frac{k}{m} + \frac{I-1}{N} + \left[\frac{\Delta M_p}{360} + \frac{\Delta\Omega}{S_t} \right] \right\} \quad (7)$$

with $p = 2, \ldots, P$.

If the patterns are superimposed properly, the minimum grid spacing at the end of the repeat interval would be reduced to $S_t /(P \bullet lcm)$ 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:

$$\frac{1}{P} = frac\left[lcm\left(\frac{\Delta M_p}{360} + \frac{\Delta\Omega}{S_t} \right) \right] \quad (8)$$

The grid will be composed by ground tracks crossing the equator at different local hours (even for sun-synchronous 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 $P \bullet m/r$ and the condition for coincidence is given by:

$$0 = frac\left[lcm\left(\frac{\Delta M_p}{360} + \frac{\Delta\Omega}{S_t} \right) \right] \quad (9)$$

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.

Table 1 summarizes all the possible situations for single and multi-plane uniform homogeneous constellations.

Table 1

	r (nodal days)	S_m (km)	m/r
P (highest revisit frequency)	$lcm/P \cdot N$	S_t /lcm	$P\, m \cdot N/lcm$
P (minimum ground track spacing)	lcm/N	$S_t /P \cdot lcm$	$m \cdot N/lcm$

Figures 1 and 2 represent the repeat cycle r (nodal days) versus *lcm (N, m)* for different numbers of the evenly deployed satellites for a single plane and a two-plane constellation minimum ground track spacing S_m (km) versus respectively whereas figure 3 shows the *lcm (N, m)* for different number of orbital planes.

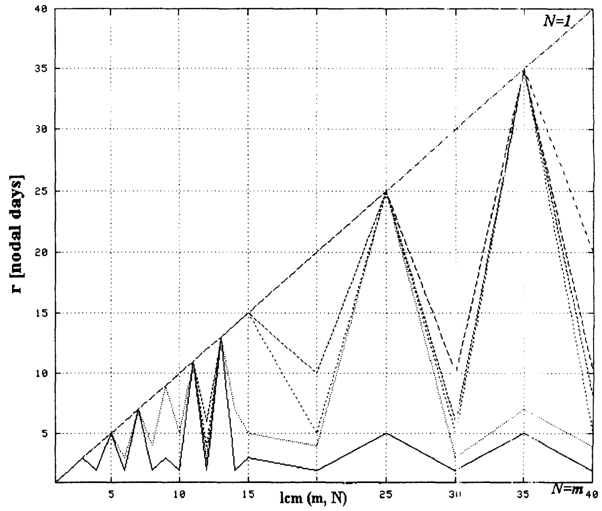

Figure 1- Repeat cycle of a single plane constellation versus *lcm* for different numbers of the evenly deployed satellites

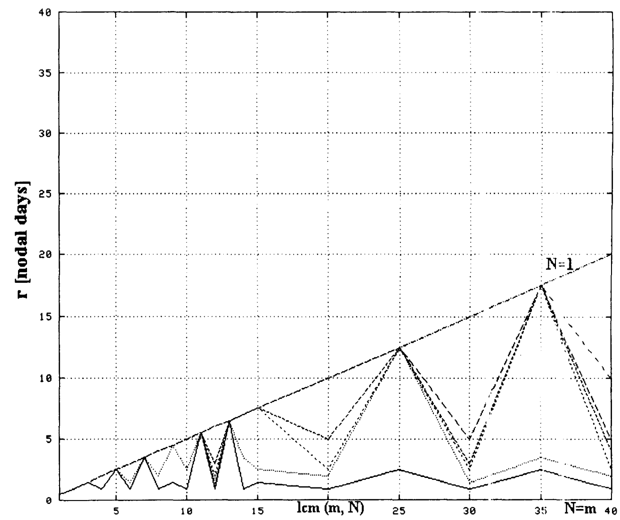

Figure 2 - Repeat cycle of two-plane constellation versus *lcm* for different numbers of the evenly deployed satellites

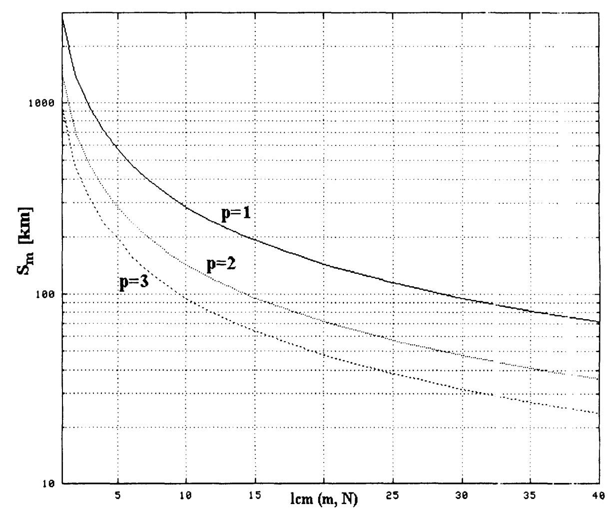

Figure 3 - Minimum ground track spacing of multi-plane constellation versus *lcm(N, m)*

Constellations for the Mediterranean Region

In order to guarantee a suitable coverage of the area of interest, a sun-synchronous orbit with an altitude of 623 km and an inclination of 97.4 degrees has been chosen as reference trajectory for the satellite constellations. Such an orbit gives rise to a repetitive ground track with a revisit interval of 5 days and a separation between two subsequent ground tracks of $S_t = 2707$ km at the equator.

A minimum baseline configuration could be assumed by $N=5$ coplanar satellites equally spaced along the orbit at intervals of 72 degrees in true anomaly; this configuration assures, according to Table 1 for $P=1$, a $S_m = S_t/5 = 542\ km$ and a repetitivity of $r=1$ day.

These characteristics can be improved simply adding a second orbital plane with five more evenly spaced satellites; this second plane could have $\Delta\Omega = 120°$ and $\Delta M = 24°$ if a low revisit interval is required or $\Delta\Omega = 60°$ and $\Delta M = 12°$ for a minimum ground track spacing.

Figures 4 and 5 respectively show the ground track pattern for these two possible configurations of the chosen two-plane constellation; each trace is numbered according the number of satellites of the constellation (first figure from 1 to 10) and the number of passes. For the purposes of the study, the ASI

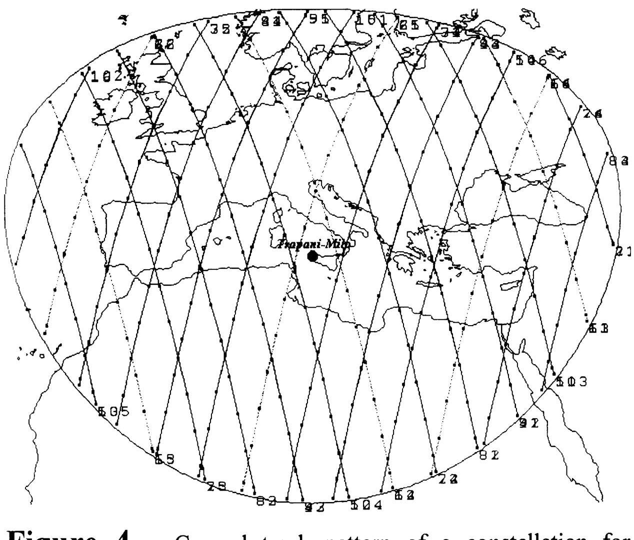

Figure 4 - Ground track pattern of a constellation for mediterranean coverage with: $P=2$, $N=5$, $m=5$, $lcm=5$, $\Delta\Omega=120$, $\Delta M=24$ (highest revisit frequency).

Trapani-Milo ground station, located in the middle of the Mediterranean area, has been chosen. Two or more plane constellations could have more than one satellite in visibility of the station, requiring either more dedicated antennas or a real-time choise among transmitted data (Ref. 6).

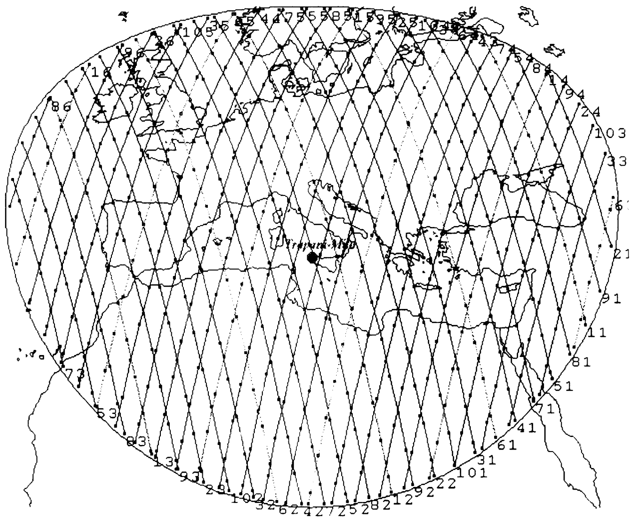

Figure 5 - Ground track pattern of a constellation for mediterranean coverage with: $P=2$, $N=5$, $m=5$, $lcm=5$, $\Delta\Omega=60$, $\Delta M=12$ (minimum ground track spacing).

Other orbits than sun-synchronous were proposed (i.e. multi-sun-synchronous) as reported in previous papers (Ref. 4, 5, 6).

Conclusions

The paper describes an orbit design analysis oriented to obtain efficient revisit coverages and repeat cycles by instruments embarked on satellites deployed on different orbital planes. This analysis is limited to uniform constellations and equally spaced satellite ground tracks at the end of the observation repeat interval.

If the patterns are superimposed properly, it is possible either to reduce the minimum grid spacing or to increase the revisit frequency on the same trace.

A specific mission for the Mediterranean area was outlined, considering a sun-synchronous orbit as a baseline.

Aknowledgement

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