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Determination of Coverage Oscillation for Inclined Communication Satellite

İbrahim ÖZ*[1], Ümit Cezmi YILMAZ[2]

Abstract

The communication engineers need to evaluate footprint movement to deploy a ground station. Geostationary communication satellite's inclination angle causes the movement of a satellite footprint. The calculation of the inclination angle requires complex astronomical knowledge and mathematical calculations. On the other hand, a satellite communication engineer does not need a very accurate inclination angle value to design a ground station for required service availability. We propose a practical method called trigonometric curve fitting for the inclination to solve the problem. The past and the future value of inclination can be evaluated by using the curve-fitting method. It is a simplified practical method and does not need advanced orbital dynamics knowledge. The orbit geometry and evaluated inclination angle are used for estimation of a coverage area movement. A satellite communication engineer can evaluate coverage area oscillation quickly and design a better link for an inclined orbit satellite by using the proposed method. We have evaluated the inclination angle of the communication satellite Sat-1 with the proposed method. Sat-1 spot beam movements and wide beam coverage area movements are estimated to obtain EIRP and G/T fluctuation for link budget purposes. The proposed method provides the results that are consistent with the results of measurements and the results of satellite operators' professional tools.

Keywords: coverage oscillation, geo satellite, communication, inclination, curve fitting

1. INTRODUCTION

Geostationary (GEO) satellites are placed into the orbit with 35786 km altitude above the equator. This orbit is called Clarke belt, and the satellites on this orbit have the same revolution period with the earth rotation. GEO satellites seem to be fixed from the earth [1]. The users can have full time transmit/receive ability with a satellite by using simple non-tracking, fixed antenna. GEO satellites called communication satellites' primary services are television broadcasting, internet, telephone, and military applications. GEO communication satellites, although they are named as "geostationary," they are not entirely stable in space. The perturbing forces that cause the satellite orbit motion to deviate from an ideal theoretical orbital motion. The sun and the moon gravitational forces, non-uniform mass

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distribution of earth, solar pressure, and electromagnetic are primary perturbing forces act on a GEO satellite [2-5]. GEO satellites have two types of movements under the external forces. The first is north-south (N/S) oscillation and the second is to drift east or west (E/W) direction to the closest stable longitude.

Maneuver compensates perturbing forces acted on a satellite. North-south station keeping (NSSK) and east-west station-keeping (EWSK) maneuvers are performed periodically to keep a communication satellite within a defined control window. NSSK maneuver controls the inclination angle and consumes much more propellant than EWSK maneuvers. It is about 20-24 times more propellant consumption than EWSK maneuvers [6-8]. EWSK maneuver controls longitudinal drift and eccentricity.

GEO satellite lifetime is calculated by taking available fuel disregarding equipment and subsystems' lifetime. Aging GEO satellite lifetime can be extended by performing only the EWSK maneuver to use the remaining limited amount of fuel more efficiently. The satellite operators decide to stop the NSSK maneuvers to extend the lifetime of a communication satellite for several years. In this case, satellites become operated in an inclined orbit. A geosynchronous orbit with a non-zero inclination is defined as inclined geosynchronous orbit (IGSO). Fixed ground stations cannot track IGSO satellites all day. Ground stations that have tracking system can track the IGSO satellites all day [9,10]. The operators offer special services via IGSO satellites. The IGSO satellites provide services to stations that have tracking capability. Customers or users access special services such as short time satellite newsgathering, point-to-point data transmission.

The IGSO satellite's inclination increases gradually by time but communication payload continues to operate, with some loss of performance at some parts of the coverage beams. Another issue satellite no longer always point accurately because of inclination at the boresight on the ground all of the time. IGSO satellite coverage beams movement follow the satellite inclination angle. This movement is basically in the north-south direction and sinusoidal. It is period is equal to the satellite period which is 24 hours. Oscillating coverage beams cause signal degradation even service interruption at certain time interval and some parts of coverages [1,8-10].

The footprint or coverage area of a communications satellite is the ground area that a satellite transmits and or receives signals within that area. Each satellite transponders or group of transponders offers different footprint maps to provide services to the desired customer area. Wide coverage area is ideal for transmitting signals over a vast geographical area while spot beam provides high power signals over small size area.

The product of transmit antenna gain and the maximum RF power per transponder defines the most important technical parameters of a communication satellite, effective isotropic radiated power (EIRP). The relative gain to noise temperature ratio (G/T) defines the receive performance of a communication satellite. These two main parameters contour values inside coverage map identify signal levels and provide information about requirements of ground system. Unfortunately, coverage contour follows satellite movement, and EIRP and G/T values are subject to change at earth fixed ground station point.

This paper aims to determine a coverage beam movement of IGSO satellite to support satellite communication engineers about EIRP and G/T margins. EIRP and G/T level vary due to inclination. The variation must be considered to have a successful transmission of signals. Satellite communication engineers can design better satellite links by having signal fluctuation levels and related link budget margins. On the other hand, the calculation of the Keplerian parameters, including the inclination angle, requires complex astronomical knowledge and mathematical calculations. The development of a new method simplifies the estimation of the inclination. A new method proposed to evaluate the inclination angle and related coverages oscillation to achieve the goal. The trigonometric curve fitting method (CFM) applied to the inclination data, and we obtain the inclination as a function of time. The method simplifies the calculation for the prediction of the inclination angle and related coverage movement.

ITU-R requirement is to operate a communication satellite within a ±0.1° control window in N/S and E/W direction. This ±0.1° control window allows the operator about 11 km daily oscillation on satellite beams. That is why, for the proposed method presented in this work, 11 km has been chosen as success criteria.

2. INCLINATION ANGLE and COVERAGE OSCILLATION RELATION

The inclination angle is one of the six Keplerian orbital parameters, which defines the angle between the equatorial plane and satellite orbital plane. Figure 1 below shows an illustrative image of earth equatorial plane and satellite orbital plane with inclination. Satellite inclination causes to move satellite in N/S direction. The period of that sinusoidal oscillation is the same as the satellite revolution period 24 hours (1436,7 minutes). We assume a satellite at zero latitude at time T_0, and then it reaches maximum inclination value at T_0+6h and T_0+18h. A satellite crosses the earth equator twice a day. Satellite completes its' 12 hours' revolution over the northern hemisphere and another 12 hours over the southern hemisphere due to the inclination angle [8,11-13]. Figure 3 shows satellite inclination angle instantaneous values for 1°, 3°, and 5° inclination over one revolution period. IGSO satellite ground track is the path followed by the sub-satellite points.

The altitude and the latitude of a satellites influence the ground track figure8-shape. IGSO satellite ground track shape is like figure-8 shape. The typical figure-8 shape of the GEO circular orbit (zero eccentricity) is shown in Figure 2 Increased eccentricity distorts the figure-8 shape. The view of figure-8 shape depends on earth station latitude. If figure-8 shape midpoint is on the higher or lower altitude instead of being on the equator then, the view of figure-8 shape is distorted. The slender and very long or asymmetric figure-8 shape can be observed at higher latitudes.

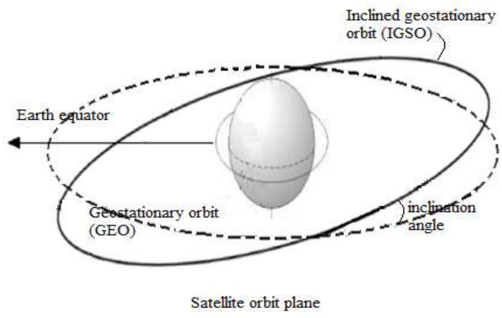

Figure 1 GEO inclination angle (the angle between the earth equator plane and satellite orbit plane)

The sub-satellite point over the earth follows the deviation in the longitude and latitude values of a communication satellite. The coverage pattern moves with the satellite inclination in both N/S and E/W direction, as shown in Figure 2. Satellite and coverages draw a figure-8 shape over a day, as shown in Figure 4. The width of the figure-8 shape depends upon E/W oscillation, while the height of the figure-8 shape depends upon N/S oscillation. The sub-satellite points of an IGSO satellite N/S oscillation exactly follow the inclination angle. Sub-satellite points E/W oscillation due to inclination is negligibly small for the eccentricity close to zero [4,14]. That's why in this study, E/W oscillation is not considered.

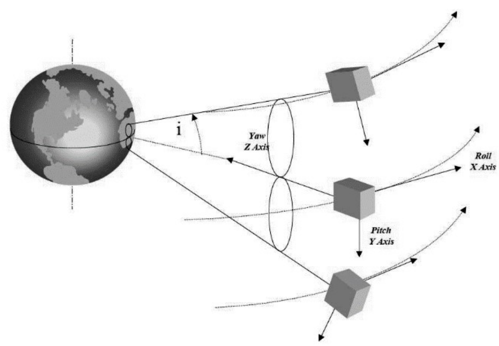

Figure 2 Satellite pointing in inclined orbit configuration, sub-satellite points over the earth, and daily figure-8 shape due to inclination

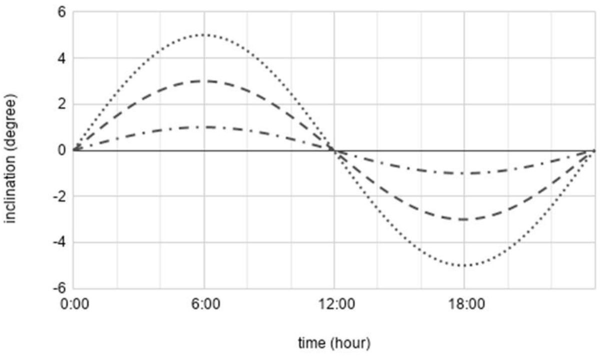

Figure 3 Satellite GEO satellite variation of inclination angle for 1°, 3° and 5° over one revolution period (one sidereal day)

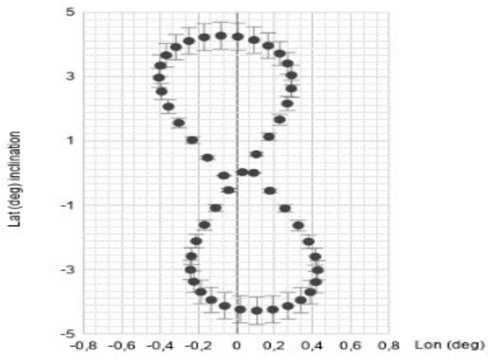

Figure 4. Diurnal movement of an inclined orbit satellite figure-8 shape over one sidereal day (ground track of IGSO), not to scale

Satellites ground stations have many types according to ITU-R regulations. Satellite ground stations may have satellite tracking capability or may have fixed antenna dishes according to the regulations. Fixed ground stations (antenna has no satellite tracking capability) have antenna mechanical misalignment due to inclination. Those misalignments are out of our study. So we neglect the signal change due to antenna misalignment. We assume the ground station's antenna has satellite tracking capability, and the antenna can track the satellite correctly. In this case, the only movement of the coverages is considered due to the inclination and neglecting other effects. The movements cause a signal change in both uplink and downlink for the ground station. Now, we can consider only uplink and downlink signals fluctuation due to the inclination angle. This oscillation affects satellite EIRP and G/T performance. The effect can be assessed as a loss in satellite performances at the Centre of Coverage (CoC) and the Edge of Coverage (EoC) as shown in the following (Equation 1) to (Equation 4):

$$\Delta G_c = EIRP_{initial} - EIRP_{final} \tag{1}$$

$$\Delta G_E = EIRP_{initial} - EIRP_{final} \tag{2}$$

$$\Delta G_c = G/T_{initial} - G/T_{final} \tag{3}$$

$$\Delta G_E = G/T_{initial} - G/T_{final} \tag{4}$$

where;

ΔG_c : Gain Loss at the center of coverage (CoC) due to a coverage movement

ΔG_E : Gain Loss at the edge of coverage (EoC) due to a coverage movement

Satellite coverage areas follow the sub-satellite point's sinusoidal movement. The fluctuation in EIRP and G/T effect ground station sizing and availability of transmission. The primary ground station sizing contains antenna diameter and high power amplifier size. A communication engineer must consider other ground station devices such as up or down converters, low noise amplifiers, waveguides, couplers, attenuators, and their losses to perform accurate and optimized link budget.

3. TRIGONOMETRIC CURVE FITTING METHOD (CFM) AND INCLINATION

The GEO satellites are under the perturbing forces such as the sun and the moon gravitational forces, non-uniform mass distribution of the earth, solar pressure, electromagnetic forces, planets, and other stars gravitational forces, etc. The sun and the moon and earth gravitational forces have large magnitude and primary contributors to the satellite orbit perturbations. The remaining perturbing forces have small effects. When all contributors are taken into account the calculation of the inclination angle becomes very complex. There are many approaches to evaluate the inclination angle accurately [1]. However, if the inclination angle is not used for satellite control purposes such as maneuver planning, conjunction analysis, etc., the evaluation may be simplified and customized for new purposes.

The inclination angle of a GEO satellite depends on time. It's main characteristics are; it has annual increment between 0.75^{o} and 0.95^{0} depending on the year, it has a magnitude up to 15 degrees [1,9,14] depending on the high area to mass ratio, and it has 18.6 years period because of the moon and the sun orbits and their gravity forces [9].

The periodic motions that have sinusoidal characteristics have been used for most of the approximations in astronomy and orbital motions. The trigonometric curve fitting method (CFM) expresses the periodic oscillation phenomena and movements effectively. The trigonometric curve fitting is a new method to evaluate the inclination angle. The CFM is the process of constructing a curve or mathematical function that has the best fit to a data set. In numerical trigonometric curve fitting technique, the sum of sines models fits periodic functions and given by,

$$f = \sum_{j=1}^{n} a_j \sin(b_j x + c_j) \tag{5}$$

In this study, we applied the CFM to inclination angle data sets, and we determine the inclination angle behavior of communication satellites. We obtained data sets from actual measurements of the inclination angle of the satellite and theoretical propagated results of the tool. These propagated values are taken from the focusgeo program, which is the software provided by GMV and commonly being used among the satellite operators, including TURKSAT. This professional tool determines the orbit of the satellite by using a series of numeric integrations and plans the control maneuvers and their firing durations as well as directions. The measured and propagated data sets have been processed, and the inclination equation and its correlation coefficient were obtained. Among different curves, the following (Equation 6) has been obtained;

$$i_{annual} = 0.097 sin\,(0.3378t + 2.538) + 0.856 \tag{6}$$

where i: inclination angle in degree/year,
t : the yearly inclination angle variation to be calculated (like 2020, 2021 etc).

The (Equation 6) correlation coefficient is 0.9963 compared to the theoretical inclination results. Figure 5 shows the behavior of the inclination for each year from 1970 to 2040 and the relationship between theoretical values and the curve fitting results.

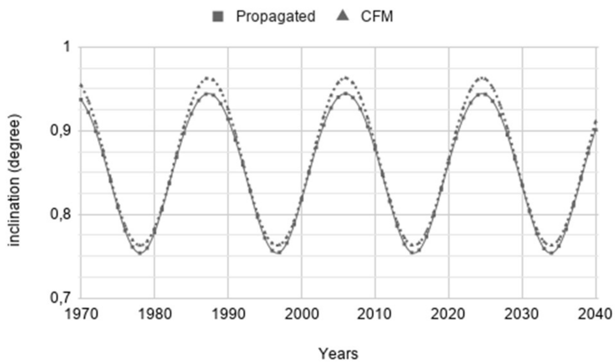

Figure 5 Comparison of proposed calculation and theoretical inclination

The formula is given in (Equation 7) starts with January 1st of each year. Accumulated inclination angle can be calculated by integrating the (Equation 6) and, as shown in (Equation 7);

$$\Delta i = \frac{\partial i}{\partial Y} \int_{T0}^{T1} i_{annual} dt + i_{initial} \tag{7}$$

where: T_0 and T_1 are the dates in decimal (for example 30 June 2020 =2020.5).
$T_{0:}$ the date of the final inclination control maneuver,
$T_{1:}$ the day of inclination angle calculated,
$i_{initial}$: the initial inclination at T_0.

(Equation 8) can be derived from the geometry, which takes into account the radius of the earth, R_e, as 6378.1 km to calculate the final oscillation of the spot beam in N/S direction.

$$ns_{osc} = iR_e \frac{\pi}{180} \tag{8}$$

where: ns_{osc} beam movement of a satellite in km.

The inclination not only causes oscillations in N/S direction, but it also causes footprint movement in E/W direction due to conservation of the angular momentum as per Kepler's Second Low and due to the Earth obsoleteness. Considering the earth radius seen from GEO orbit is 8.6708 degrees (which is about 0.151 rad) and by using the polar radius of the earth (R_p), which is about 6356.8 km. Similarly, from the geometry, the oscillation at E/W longitude sinusoidal half width oscillation due to inclination and for zero eccentricity can be calculated, as shown in (Equation 9).

$$ew_{osc} = (atan(\frac{1}{2}\sqrt{\sec(i)} - \sqrt{\cos(i)})R_p \frac{\pi}{180} \quad (9)$$

E/W oscillation due to 1° , 3° and 5° inclinations are 0.004°, 0,039°, 0.109° respectively. Circular orbit (eccentricity very close to zero) IGSO satellites E/W oscillation due to inclination is negligibly small and has minor effect on EIRP and G/T. That is why in this study, E/W oscillation effects on signals level are not considered. The N/S oscillation caused by the inclination moves the coverages from its zero inclination position. Figure 6 shows the boresight movement in terms of km for 3° inclination. Its maximum displacement is around 334 km when the satellite is at the north and the south peak latitude. Larger inclination causes more displacement and more magnitude of oscillation.

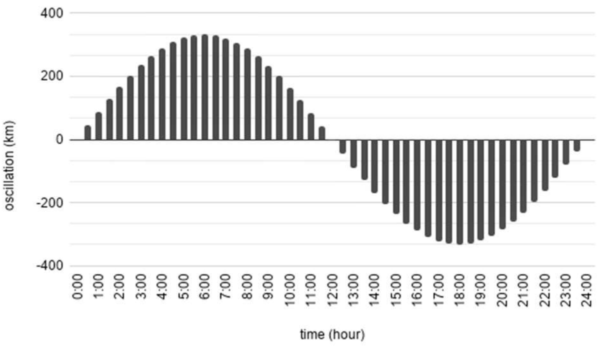

Figure 6 GEO satellite at 3-degree inclination, coverage movement in km for 24 hours' period

3.1. Sat-1 Communication Satellite at IGSO

We have selected Sat-1 communication satellite as an illustrative example. Sat-1 wide area coverage and spot beam are examined to verify signal fluctuation. A satellite spot beam and wide beam have different oscillations in terms of signal fluctuation level. Similarly, coverages at the equator and coverages at the higher altitude have different behavior in terms of E/W oscillation. However, the oscillation in the E/W direction was not considered because of explained reasons. We selected two ground stations as a reference. The first CoC site is in the middle of the spot beam at 32.00° E longitude and 40.00° N latitude while the second reference is EoC site, and it is at 32.00° E longitude and 35.00° N latitude. Figure 7 below shows the spot beam examples on Sat-1 satellite at 42.00° East longitude and in 0°, 1°, 5°, -3°, -1°, and -5° inclinations. The "+" sign shows the antenna boresight, and the contours show the center of coverage, mid of coverage, and the edge of coverage from inner contour to outer contour, respectively. The boresight has peak EIRP and G/T values while the outer contour has 20 dB gain loss compared to the peak value. Outside of the outer contour is assumed to be out of service area. The movement due to inclination is shown in Figure 7 for the Turkey spot beam of Sat-1. Figure 7 shows inclination maximum and minimum values i.e Sat-1 at T_0+6 and T_0+18 hour. The coverages are in between those two places and draw the sinusoidal figure, as shown in Figure 2.

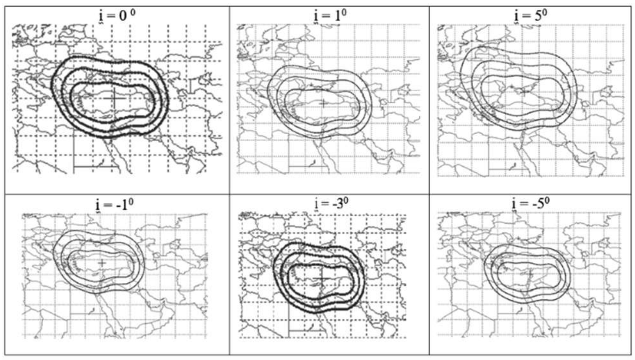

Figure 7 Sat-1 spot beam movement for 0° ,1°, 5°, -3°, -1° and -5° inclination, from satellite @42° East

Figure 8 below shows the wide beam examples on a Sat-1 satellite at 42.00° East longitude and in 0°, 1°, 5°, -3°, -1°, and -5° inclination. We selected two ground sites as a reference to calculate signal level fluctuation. The CoC site is in the middle of the wide beam at 32.00° E longitude and 40.00° N latitude while the second reference is EoC site, and it is at 38.00° E longitude and 24.00° N latitude. Similarly, "+" shows boresight of the satellite antenna, and the contours show the center of the coverage, mid of the coverage, and the edge of the coverage from closed inner to outer line, respectively. The boresight has peak EIRP and G/T values. The outer contour has 20 dB gain loss. We assume inside of the outer contour is the service area of the Sat-1. The inclinations 1° and 5° show Sat-1 at time T_0+6 hour while the inclination -1°, -3°, and -5° show Sat-1 at time T_0+18 hour.

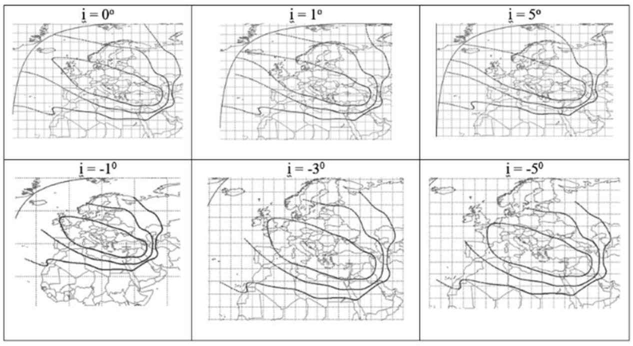

Figure 8 Sat-1 wide beam movement for 0^0, 1^o, 5^o, -1^o, -3^o and -5^o inclination, from satellite @42° East

The Figure 7 and Figure 8 coverage contours are taken from actual Sat-1 antenna pattern data. The measured and propagated inclination angle effects on the Sat-1 spot beam (small size coverage) and wide beam (large size coverage) show coverages movement at north peak and south peak inclination compared to reference zero inclination. Those figures show 1 cycle oscillation. The beam's complete cycle oscillation is fully interpreted by combining Figure 3 with Figure 7 and Figure 8.

4. RESULTS AND DISCUSSION

We have obtained the inclination values with the CFM for future and past. Those results first compared with the measured data of in orbit satellite. The actual measured data has been taken from the TURKSAT Sat-1 satellite. This satellite last N/S maneuver was performed on July 18th, 2008, and then the satellite was left in inclined orbit operation. The second column of Table 1, shows the measured inclination angle of Sat-1 at different times. The measured inclination angle of the satellite data was acquired from the Sat-1 orbit measurement's value from the satellite control center. The CFM column shows the results evaluated with the proposed method. The comparison of measured and CFM results are very close to each other. As can be seen in the last column, the differences are always less than 9 km. The measured data of the inclination and the evaluated data of the inclination mean difference is 0.038°, which is about 4.23 km. So the results obtained from the CFM are in very good agreement with the results of measurements.

Table 1
Comparison with Sat-1 measured and proposed CFM inclination values, T_o: 19.05.2008, initial inclination 0.153°

T	Inclination M.	Inclination CF	Δi	ns_{osc} (in km) M.	ns_{osc} (in km) CF	Δns_{osc} km
25.09.2008	0.49	0.48	0.018	55.3	53.3	1.98
18.12.2008	0.72	0.69	0.026	79.7	76.8	2.91
26.02.2009	0.91	0.87	0.044	100.9	95.9	4.92
24.09.2009	1.40	1.38	0.024	156.2	153.5	2.71
03.12.2009	1.58	1.55	0.034	176.2	172.5	3.82
11.03.2010	1.83	1.79	0.049	204.1	198.7	5.49
29.07.2010	2.19	2.12	0.074	244.0	235.8	8.25

Table 2 shows the theoretical propagated inclination angle of Sat-1 for the past. The past years propagated inclination data are obtained from the tool by running the software backward in time. The CFM column shows the results evaluated with the proposed method in a backward direction in time. The comparison of theoretical propagated and CFM results are very close to each other. As the results can be seen in the last column, the differences are always less than 9 km. The propagated data of the inclination and the evaluated data of the inclination average difference is 0.038° that is about 4.23 km.

Table 2
Comparisons with propagated (p) and curve fitting (CF) method in backward direction, T_0=01.01.2000 and initial inclination 0.001°

T	Inclination P.	Inclination CF	Δi	ns_{osc} P.	ns_{osc} CFM	Δns_{osc} (km)
19.07.2000	0.46	0.45	0.0063	51.3	50.61	0.70
04.02.2001	0.92	0.92	0.0036	102.3	101.89	0.40
23.08.2001	1.38	1.39	0.0066	153.8	154.51	0.73
11.03.2002	1.85	1.87	0.0174	206.3	208.23	1.94
27.09.2002	2.31	2.36	0.0503	257.4	262.99	5.59
15.04.2003	2.80	2.86	0.0665	311.3	318.72	7.40
01.11.2003	3.29	3.37	0.0807	366.3	375.30	8.98

Table 3 shows the future theoretical propagated inclination angle of Sat-1. Those data are obtained from the focusgeo tool by running the software forward in time, and we get the next year's estimated inclination angle values. The CFM column shows the results evaluated with the proposed method in the forward direction in time. The comparison of the theoretical propagated and

CFM results are very close to each other. As the results can be seen in the last column, the differences are always less than 9 km. The propagated data of the inclination and the evaluated data of the inclination average difference is 0.032^0 that is about 3.56 km.The differences between the results of CFM and other methods are all less than 0.1o and less than 11 km, which is the success criteria.

Table 3
Comparisons with propagated and proposed method in forward direction, T_0=01.01.2020 and initial inclination 0.001°

T	Inclination P.	Inclination CF	Δ*i*	nsosc (in km) P.	nsosc (in km) CF	Δnsosc (km)
19.07.2020	0.48	0.48	0.001	53.2	53.3	0.09
04.02.2021	0.97	0.97	0.001	107.5	107.3	0.14
23.08.2021	1.46	1.46	0.004	162.2	162.6	0.47
11.03.2022	1.94	1.97	0.025	216.1	218.8	2.74
27.09.2022	2.43	2.48	0.052	270.1	275.9	5.73
15.04.2023	2.93	2.99	0.063	326.5	333.5	6.97
01.11.2023	3.43	3.52	0.085	382.2	391.6	9.41

We can study the inclination angle effects on satellite communication performance. To analyze the effects, we have a communication satellite illustrative examples that are for inclination 1°, 3°, and 5° cases.

The IGSO satellites are generally multi-beam satellites. When a satellite moves due to inclination, all coverages move together with satellite. Coverage movement due to N/S oscillations influences satellite communication performances. We assume the sub-satellite point is on the equator at T_0 in this case satellite operates like in geostationary operation. However, at the T_0 +6 h satellite reaches maximum inclination value on the northern hemisphere, the coverages move the north, and maximum displacement occurs with respect to zero inclination nominal operation status. Satellite continues its movement and T_0+18 hour; it reaches maximum inclination value in the southern hemisphere, again the maximum coverages displacement occurs with respect to zero inclination but in the opposite direction in this case. Satellite coverages movement follows the sinusoidal movement, as shown in Figure 2. Consequently, the satellite's EIRP and G/T fluctuate due to the inclination. These oscillations influence satellite transmit EIRP and satellites receive G/T.

We assume the edge of coverage ground station is at the southern part of the contour. In this case, EIRP and G/T values first increase and then decrease for negative inclination values. Table 4 shows spot beam EIRP and G/T fluctuation for Sat-1 IGSO satellite. Center of the coverages EIRP and G/T changes due to 3^0 inclination is about 1.5 dB. Edge of coverages EIRP and G/T fluctuation due for 3° inclination is about 4.5 dB.

Table 4
Sat-1 Spot beam EIRP G/T variation due to the given inclination angles

i	EIRP CoC	EIRP EoC	G/T CoC	G/T EoC	Δ EIRP CoC	Δ EIRP EoC	Δ G/T CoC	Δ G/T EoC
0°	53.53	43.03	11.28	-7.77	0.00	0.00	0.00	0.00
1°	52.99	40.98	11.28	-8.77	-0.54	-2.05	0.00	-1.00
3°	51.41	36.31	9.73	-12.77	-1.58	-4.67	-1.55	-4.00
5°	49.66	30.66	9.23	-18.82	-1.75	-5.65	-0.50	-6.05
-1°	52.67	36.67	11.01	-6.71	3.01	6.01	1.78	12.11
-3°	51.31	41.82	9.79	-8.59	-1.36	5.15	-1.22	-1.88
-5°	49.44	29.35	9.41	-12.91	-1.87	-12.47	-0.38	-4.32

Similarly, Table 5 shows wide beam EIRP and G/T fluctuation for Sat-1 IGSO satellite. CoC EIRP and G/T changes due to 3^0 inclination is about 1.5 dB. This value is very good. Edge of coverages EIRP and G/T fluctuation due to 3° inclination is about 3 dB.

Table 5
Sat-1 Wide beam EIRP G/T variation due to the given inclination angles

i	EIRP CoC	EIRP EoC	G/T CoC	G/T EoC	ΔEIRP CoC	ΔEIRP Eo)	Δ G/T CoC	Δ G/T EoC
0°	51.14	37.59	4.84	-9.54	0.00	0.00	0.00	0.00
1°	50.60	35.62	4.56	-11.51	-0.54	-1.97	-0.28	-1.97
3°	49.01	32.01	3.35	-15.12	-1.59	-3.61	-1.21	-3.61
5°	47.27	28.61	2.83	-18.52	-1.74	-3.40	-0.52	-3.40
-1°	50.28	36.51	4.59	-10.62	3.01	7.90	1.76	7.90
-3°	48.92	41.61	4.51	-13.52	-1.36	5.10	-0.08	-2.90
-5°	47.05	37.57	3.12	-17.56	-1.87	-4.04	-1.39	-4.04

The daily coverages oscillation of an IGSO satellite can be determined practically to understand the EIRP and G/T fluctuation at the earth station at CoC and EoC. The earth stations at EoC, are more affected than the stations at the CoC. Additional power requirement of 3 dB due to coverage movement implies to have double HPA size or implies to have larger size antenna. The users may not request 24 hours uninterrupted transmission; in this case, the communication engineers may prepare a part-time transmission plan by using daily EIRP and G/T fluctuation.

EIRP and G/T values evaluated with the CFM and other method are shown in Table 6. Referring EIRP and G/T change to compare the methods, it is about 10^{-4} or 10^{-3} dB. These values have no practical meaning in terms of antenna diameter and HPA size.

Table 6
The difference of inclination angle average and standard deviation values for the CFM vs Measurements and the CFM vs Forward propagation

	Δi CFM-Measurement	**Δi CFM-Propagated**	**ΔEIRP dB**	**ΔG/T dB/K**
Avg	0.0386°	0.0328°	$\sim10^{-4}$	$\sim10^{-4}$
Stdev	0.0192°	0.0337°	$\sim10^{-3}$	$\sim10^{-3}$

These small differences in the inclination angle of the CFM and the other methods have no effect on parameters of the link budgets. Therefore, the related earth station sizing is the same for all methods.

The communication engineers check link margins before the start of services. Satellite EIRP, G/T fluctuation due to inclination depends on coverage size and shape. Spot beams i.e., small size coverages, have more degradation in signal level and quality. The wide beams have less fluctuation and hence more degradation in signal level and quality. The edge of coverages has considerable fluctuation. Signals may not be received at the edge of the coverages in some period of day, even if ground stations entirely operated.

5. CONCLUSION

A practical simplified method was developed to estimate the coverage movements of an IGSO communication satellites. The inclination angle of a communication satellite depends many astronomical factors such as, the sun and the moon gravitational forces and the earth obsoleteness. The satellite communication engineers evaluate the coverage oscillations quickly by using the CFM. Comparisons of the CFM with real data and propagated data show that the footprint variation can be predicted better than 10 km accuracy, and this value is below the nominal daily oscillation of any GEO satellite which is controlled in ±0.1°. However, the CFM is not suitable for satellite control purposes, such as maneuver planning or conjunction analysis. The method is valid to use for a maximum duration of 27 consequential years, which means up to 15° inclination.

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The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by the authors.

Authors' Contribution

İ.Ö. and C.Y. conceived a new method to calculate inclination and to evaluate the relevant footprint movement. C.Y. developed the CFM and performed the inclination angle computations. İ.Ö. and C.Y. verified the analytical methods with practical measurements. İ.Ö. performed calculation of footprint movement and EIP and G/T fluctuation. İ.Ö. wrote the manuscript. Both İ.Ö and C.Y. contributed to the final version of the manuscript.

The Declaration of Ethics Committee Approval

The authors declare that this document does not require an ethics committee approval or any special permission.

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