Comparative coverage and horizon plane analysis for LEO, MEO, and GEO AND HEO Satellites

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***Abstract*— In this paper, comparative coverage and horizon plane analysis for LEO, MEO, and GEO and HEO satellites were studied. The focus of the study was to evaluate the variation in the percentage coverage area and horizon plane of earth orbiting satellites with respect to their orbital altitude and elevation angles. Eighteen case study satellites were selected; six from LEO satellites, five from MEO satellites, two from GEO satellites and five from HEO satellites. The six LEO satellites were studied separately while the MEO, GEO and HEO were studied together. The results showed that among the six LEO satellites considered, at elevation angle of zero degree (0º), the percentage coverage area of the earth surface for the LEO 1 satellite (Starlink-1246) with altitude of 269.62 km was 2.03 % while that of LEO 6 satellite (Globalstar M089) with altitude of 1,600.20 km was 10.03 %. Again, the horizon plane for the LEO 1 was 1874.02 km while that of LEO 6 was 4792.99 km. For the MEO, GEO and HEO satellites, the results showed that at elevation angle of zero degree (0º), the percentage coverage area for the MEO 1 satellite (SPIRALE B) with altitude of 14758.66 km was 27.55 % while that of HEO 5 satellite (TESS) with altitude of 236,454.93 km was 48.69 %. Again, the horizon plane for the MEO 1 was 25378.79 km while that of HEO 5 was 485506.32 km. In all, it was found that the maximum coverage area occur at elevation angle of zero degree (0º) and the rate of increase in orbital altitude is higher than the rate of increase in percentage coverage area of the satellites. Again, the rate of increase in horizon plane is lower than the rate of increase in the percentage coverage area. Also, at high altitude, in the case of HEO satellites, the coverage area tends to 50%.**

Keywords*— *Low Earth Orbit (LEO) Satellite, Orbital Altitude, Medium Earth Orbit (MEO), Horizon Plane, Geostationary Orbit (GEO), Coverage Area, High Earth Orbit HEO.

1. Introduction

Today, the earth is orbited by several satellites and their orbits are carefully selected to make the satellite suitable for certain given applications or to include a certain ground coverage target [1,2,3,4,5,6,7,8,9,10,11,12]. Usually, low earth orbit (LEO) satellites are good as they offer low communication delay and smaller propagation loss when compared to the medium earth orbit (MEO) geosynchronous (GEO) and high earth orbit (HEO) satellites [13,14,15,16,17,18,19,20,21]. However, the LEO satellites have smaller coverage area. Hence, when compared with the MEO, GEO and HEO satellites, the LEO satellite requires larger number of satellites in a constellation to cover the whole globe [22,23,24,25].

In practice, the coverage area of a satellite is represented in terms of the fraction of the total earth surface that is covered by the satellite [26,27,28,29]. The coverage area is usually defined with respect to a single satellite which can actually be a part of a satellite constellation [30,31,32,33]. In this wise, satellite constellation can be designed such that the cumulative coverage of the individual member satellite will be at least equal to the total earth surface area. In essence, determination of the individual satellite's coverage area is key in the design of satellite constellation for global coverage. As such, in this paper, the computation of satellite coverage area and horizon plane is presented. The horizon plane represents a flat circle which has diameter that is twice the maximum slant range of the satellite from earth station at zero elevation angle. Also, the coverage area and horizontal plane of selected LEO, MEO, GEO and HEO satellites are computed and compared.

2. Methodology

In a satellite constellation, the region on the earth surface where an individual satellite in the constellation is visible is denoted as the coverage area of that particular satellite. The coverage area of any satellite depends on certain parameters of the particular satellite orbit. In this paper, the key orbital parameters considered in the determination of the satellite coverage area are the earth radius (R_e) and satellite altitude (H_s) , as well as the elevation angle (θ_{eL}) and the slant range (d). In th1s case, the coverage area of the satellite in square kilometres denoted as Coverage Area (km^2) and in percentage of the earth surface denoted as Coverage Area (%) are computed as follows [28,34];

$$CoverageArea\ (km^2) = 2(\pi)(R_e)^2[1 - \cos(\beta)] \quad (1)$$

$$CoverageArea\ (\%) = \frac{[1 - \cos(\beta)]}{2} \quad (2)$$

Where

$$\beta = 90° - \alpha - \theta_{eL} \quad (3)$$

$$\alpha = \sin^{-1}\left\{\left(\frac{R_e}{R_e + H_s}\right)(\cos(\theta_{eL}))\right\} \quad (4)$$

The maximal coverage denoted as $CoverageAreaMax\ (km^2)$ and $CoverageAreaMax(\%)$ are obtained when the elevation angle (θ_{eL}) is zero (0).

The slant range (d) is given as a function of elevation angle (θ_{eL}) as follows [28,34];

$$d = R_e\left[\sqrt{\left[\left(\frac{R_e + H_s}{R_e}\right)^2 - \cos^2(\theta_{eL})\right]} - \sin(\theta_{eL})\right] \quad (5)$$

Again, maximum slant range (d_{max}) is obtained when elevation angle is zero ($\theta_{eL} = 0$). Hence,

$$d_{max} = R_e\left[\sqrt{\left[\left(\frac{R_e + H_s}{R_e}\right)^2 - 1\right]}\right] \quad (6)$$

The for an earth station that communicates with the satellite with altitude, H_s , the horizon plane represented as flat circle which has diameter (HP) of $2(d_{max})$. That is, [28,34];

$$HP = 2(d_{max}) = 2(R_e)\left[\sqrt{\left[\left(\frac{R_e + H_s}{R_e}\right)^2 - 1\right]}\right] \quad (7)$$

2.2 The case study LEO,MEO, GEO and HEO satellites

Eighteen case study satellites were selected from the LEO,MEO, GEO and HEO orbit categories and their names as well as some of their key parameters for the study are presented in Table 1 (for the six GEO satellites) and in Table 2 for the five MEO satellites , two GEO satellites and five HEO satellites). The data source, provided mainly the orbital period, To. As such, the orbital altitude, $\boldsymbol{H_s}$ and the semi major axis, R_s are given as follows;

$$\boldsymbol{T_o = 2\pi\sqrt{\frac{(R_e+h)^3}{\mu}} = 2\pi\sqrt{\frac{(R_s)^3}{\mu}}} \quad \textbf{(8)}$$

$$\boldsymbol{R_s = \left[\mu\left(\frac{T_o}{2\pi}\right)^2\right]^{\frac{1}{3}}} \quad \textbf{(9)}$$

$$\boldsymbol{H_s = R_s - R_e = R_e - \left[\mu\left(\frac{T_o}{2\pi}\right)^2\right]^{\frac{1}{3}}} \quad \textbf{(10)}$$

Where $\mu = 398600\ Km^3/s^2$.

The bar chart comparison of the orbital altitude for the LEO satellites is presented in Figure 1 while the bar chart comparison of the orbital altitude for the MEO, GEO and HEO satellites are presented in Figure 1. Among the LEO satellite in Table 1, Starlink-1246 has the lowest altitude of 269.62 km while Globalstar M089 has the highest altitude of 1,600.20 km. Similarly, among the MEO, GEO and HEO satellite in Table 2, the MEO satellite SPIRALE B has the lowest altitude of 14758.66 km while the HEO satellite, TESS has the highest altitude of 236,454.93 km.

Table 1 The names key parameters of the six LEO case study satellites

S/N	Name of Satellite	NORAD Number	Purpose	Type of Orbit	Period (minutes)	Hs	Rs
1	Starlink-1246	45235	Communications	LEO	89.9	269.62	6,647.62
2	KIPP-1	43157	Communications	LEO	95.3	533.23	6,911.23
3	FORTÉ	24920	Earth Observation	LEO	101	806.13	7,184.13
4	Yaogan 16C	39013	Earth Observation	LEO	106.33	1,056.71	7,434.71
5	Sentinel 6	46984	Earth Observation	LEO	112.4	1,337.03	7,715.03
6	Globalstar M089	37744	Communications	LEO	118.2	1,600.20	7,978.20

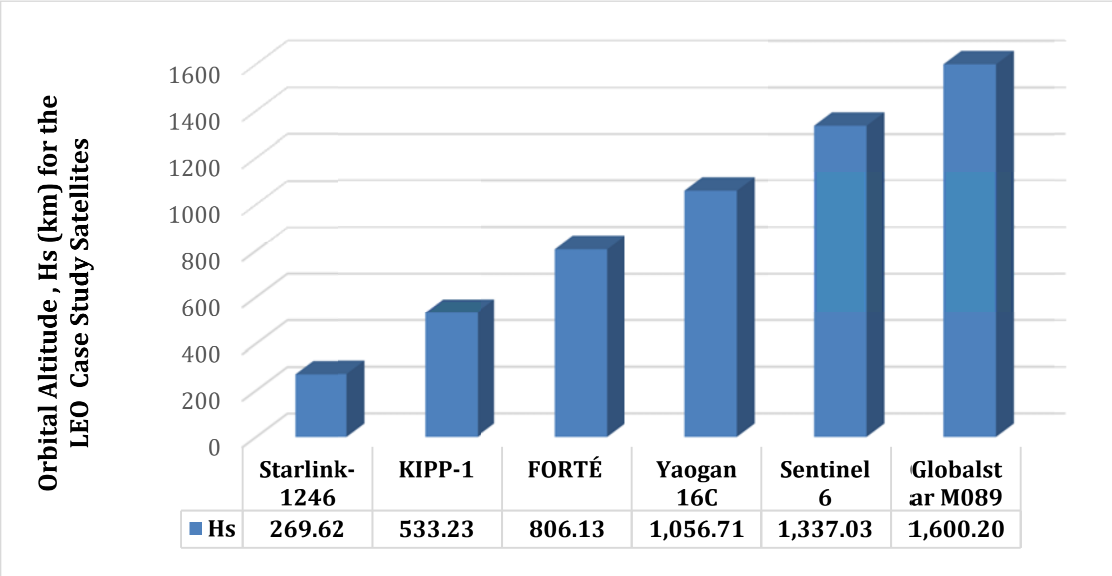


Figure 1 The bar chart comparison of the orbital altitude for the LEO satellites

Table 2 The names key parameters of the five MEO, two GEO and five HEO case study satellites

S/N	Name of Satellite	NORAD Number	Purpose	Type of Orbit	Period (minutes)	Hs	Rs
1	SPIRALE B	33752	Military	MEO	509.7	14758.66	21,136.66
2	USA 168	27704	Navigation/Global Positioning	MEO	720.65	20248.23	26,626.23
3	Galileo FOC FM8	41175	Navigation/Global Positioning	MEO	860.51	23590.43	29,968.43
4	POLAR	23802	Space & Earth Science	MEO	1109	29112.69	35,490.69
5	BSAT-3B	37207	Communications	GEO	1365.61	34,395.48	40,773.48
6	Eutelsat Quantum	49056	Communications	GEO	1436	35,784.82	42,162.82
7	CTDRS	32779	Communication	HEO	1,478.20	36,606.86	42,984.86
8	O3b FM20	44112	Communications	MEO	280.73	44112	14,202.10
9	CLUSTER II-FM6	26410	Space & Earth Science	HEO	3,260.30	66,454.65	72,833.65
10	MMS 4	40485	Space & Earth Science	HEO	5,065.50	91,322.32	97,703.32
11	OPS 6679 (VELA 8)	2766	Military	HEO	6,770.80	112,172.53	118,555.53
12	TESS	43435	Space & Earth Science	HEO	19848.6	236,454.93	242,836.93

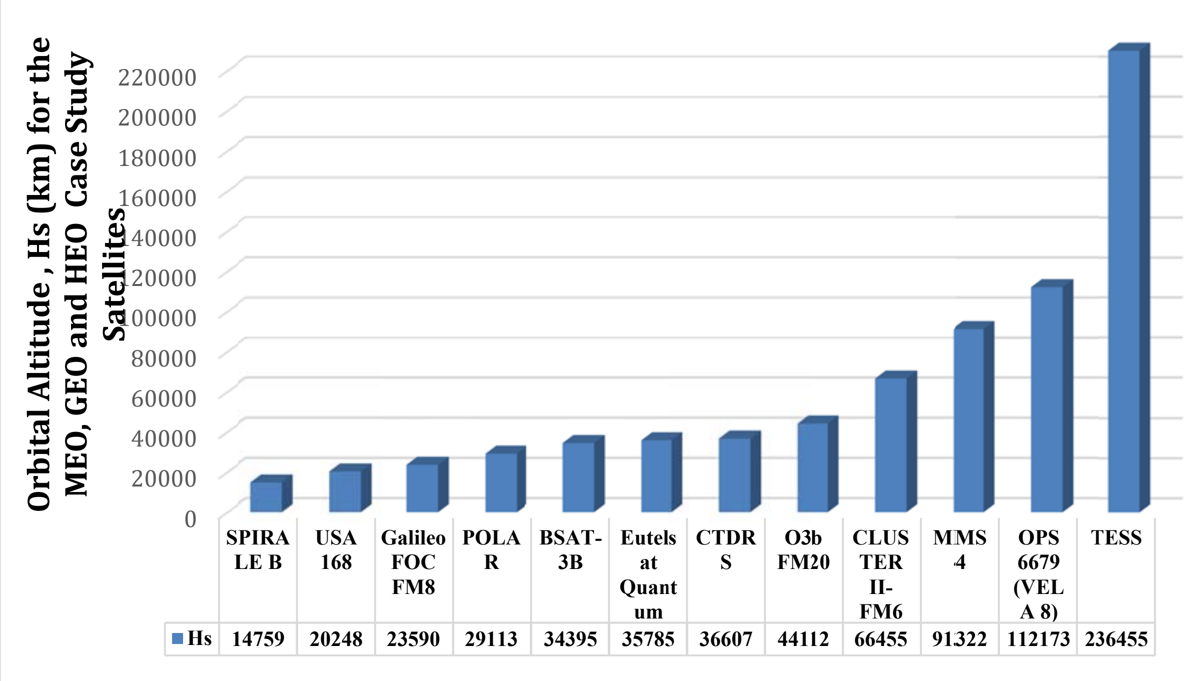


Figure 2 The bar chart comparison of the orbital altitude for the MEO , GEO and HEO satellites

3. Results and discussion

The results of the coverage area (%) versus elevation angle computations for the six LEO case study satellites are presented in Table 3 and Figure 3. The results show that for each of the LEO satellites orbital altitude, the percentage coverage area of the earth surface is maximum at elevation angle of zero degree (0º), as shown in Table 4, Figure 4 and Figure 7. Also, the coverage area decreases with increase in elevation angles but increases with increase in orbital altitude, as shown in Table 4, Figure 4 and Figure 7. At elevation angle of zero degree (0º), the percentage coverage area of the earth surface for the LEO 1 satellite (Starlink-1246) with altitude of 269.62 km is 2.03 % while that of LEO 6 satellite (Globalstar M089) with altitude of 1,600.20 km is 10.03 %.

The results of the horizon plane computations for the six LEO case study satellites are presented in Figure 5, Figure 6 and Figure 7. The results show that the horizon plane increases with increase in orbital altitude. Specifically, the horizon plane for the LEO 1 satellite (Starlink-1246) with altitude of 269.62 km is 1874.02 km while that of LEO 6 satellite (Globalstar M089) with altitude of 1,600.20 km is 4792.99 km. Again, the results of the coverage area, horizon plan and orbital altitude normalized with respect to LEO 1 show that the coverage area of LEO 6 is 4.9 times that of LEO 1, the horizon plane of LEO 6 is 2.6 times that of LEO 1, and the orbital altitude of LEO 6 is 5.9 times that of LEO 1. In essence, the increase in orbital altitude is higher than the increase in both coverage area and horizon plane.

Table 3 The results of the coverage area (%) versus elevation computations for the LEO case study satellites

Elevation angle (°)	Coverage Area (%) for LEO Satellite 1	Coverage Area (%) for LEO Satellite 2	Coverage Area (%) for LEO Satellite 3	Coverage Area (%) for LEO Satellite 4	Coverage Area (%) for LEO Satellite 5	Coverage Area (%) for LEO Satellite 6
0	2.03	3.86	5.61	7.11	8.67	10.03
2.5	1.50	3.10	4.69	6.07	7.52	8.80
5	1.11	2.50	3.92	5.17	6.51	7.70
7.5	0.83	2.01	3.27	4.41	5.63	6.73
10	0.63	1.63	2.74	3.76	4.87	5.88
12.5	0.49	1.33	2.29	3.21	4.21	5.14
15	0.38	1.09	1.93	2.74	3.65	4.49
17.5	0.30	0.89	1.63	2.34	3.16	3.92

20	0.24	0.74	1.38	2.01	2.73	3.42
22.5	0.20	0.62	1.17	1.72	2.37	2.98
25	0.16	0.52	0.99	1.48	2.05	2.61
27.5	0.13	0.44	0.85	1.27	1.78	2.27
30	0.11	0.37	0.72	1.10	1.55	1.98
32.5	0.09	0.31	0.62	0.95	1.34	1.73
35	0.08	0.26	0.53	0.82	1.16	1.51
37.5	0.07	0.23	0.45	0.70	1.01	1.31

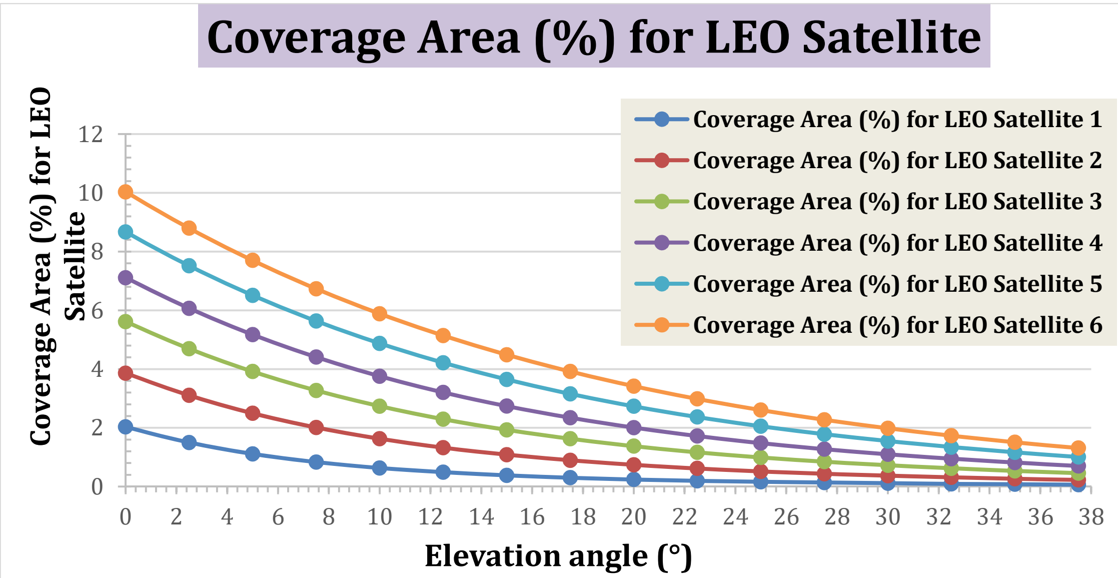


Figure 3 The coverage area (%) versus elevation graph for the LEO case study satellites

Table 4 The results of the coverage area (%) versus orbital altitude computations for the LEO case study satellites

Orbital Altitude, Hs (km)	Coverage Arear (%) for Elevation Angle, El =0°	Coverage Arear (%) for Elevation Angle, El =5°	Coverage Arear (%) for Elevation Angle, El =10°
1600.2	10.03	7.70	5.88
1337.03	8.67	6.51	4.87
1056.71	7.11	5.17	3.76
806.13	5.61	3.92	2.74
533.23	3.86	2.50	1.63
269.62	2.03	1.11	0.63

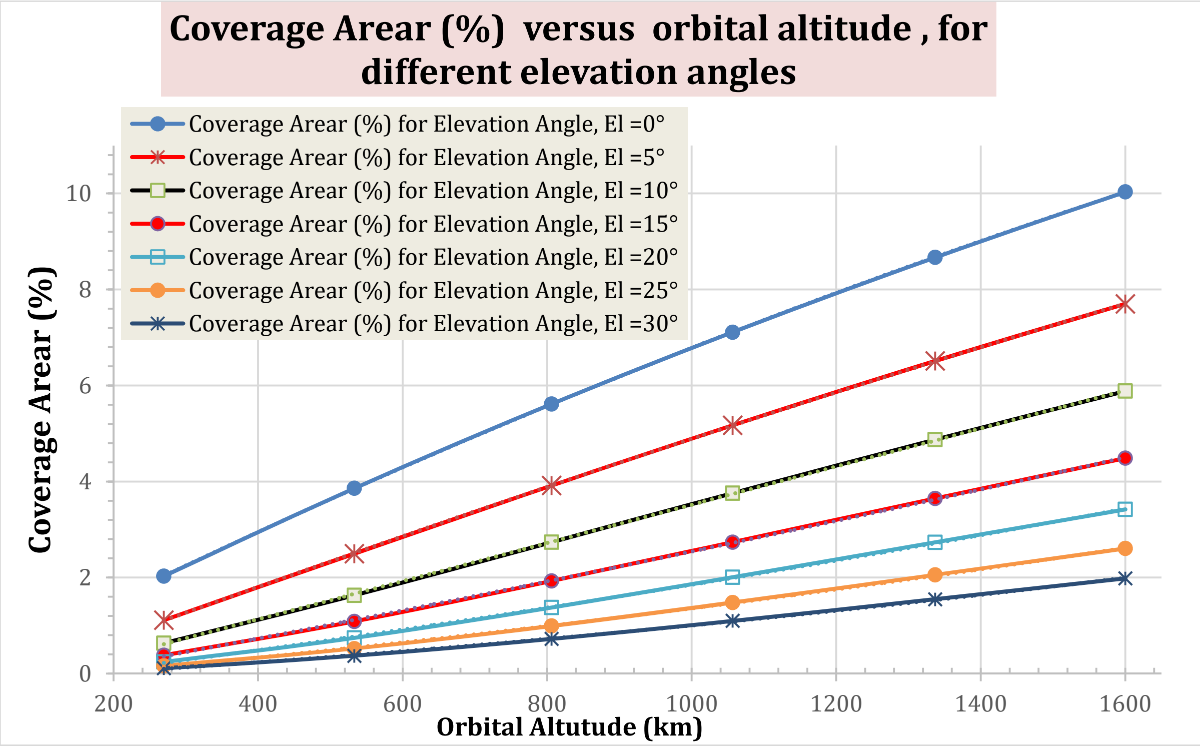


Figure 4 The coverage area (%) versus orbital altitude graph for the LEO case study satellites

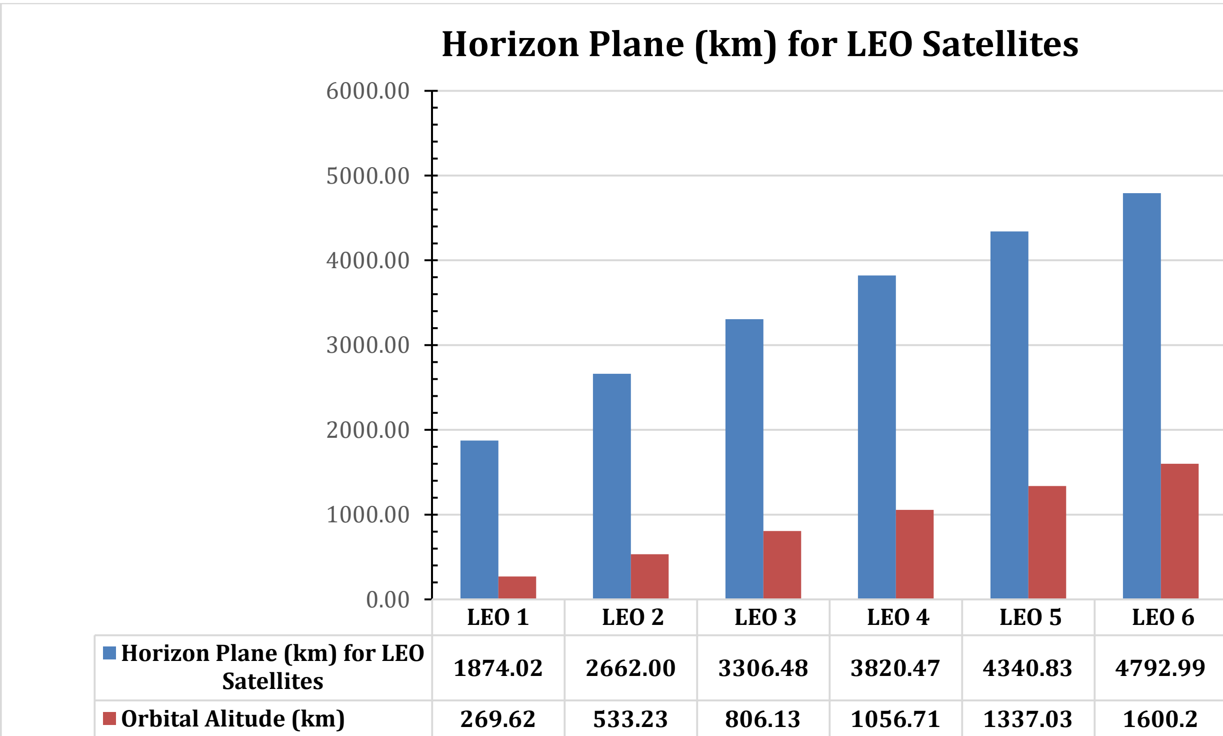


Figure 5 The bar chart of the horizon plane for the LEO case study satellites

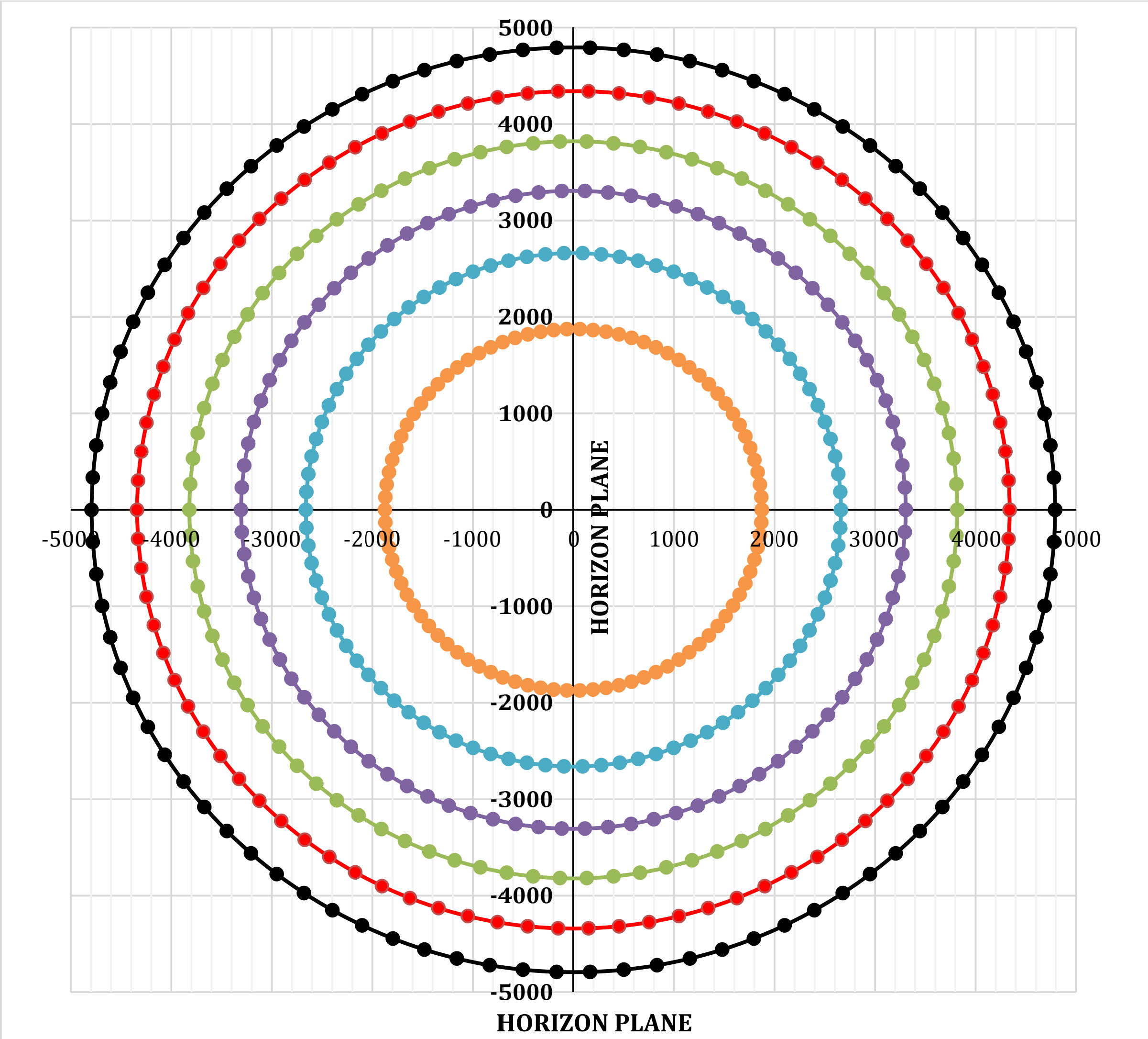
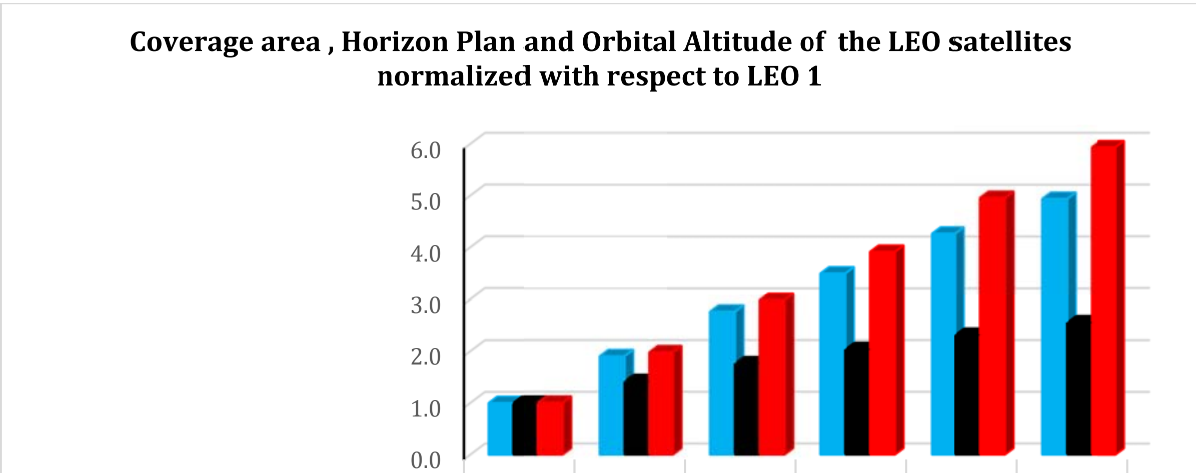


Figure 6 The radial plot of the horizon plane for the LEO case study satellites



	1	2	3	4	5	6
Coverage Area (%) normalized with respect to LEO 1 (%)	1.0	1.9	2.8	3.5	4.3	4.9
Horizon Plane normalized with respect to LEO 2	1.0	1.4	1.8	2.0	2.3	2.6
Orbital Altitude normalized with respect to LEO 1	1.0	2.0	3.0	3.9	5.0	5.9

Figure 7 The coverage area, horizon plane and orbital altitude normalized with respect to LEO 1

The results of the coverage area (%) versus elevation angle computations for the MEO, GEO and HEO case study satellites are presented in Table 5 and Figure 8. Again, the results show that for the MEO, GEO and HEO satellites, the percentage coverage area of the earth surface is maximum at elevation angle of zero degree (0°), as shown in Table 6, Figure 9 and Figure 12. Also, the coverage area decreases with increase in elevation angles but increases with increase in orbital altitude, as shown in Table 6, Figure 9 and Figure 12. At elevation angle of zero degree (0°), the percentage coverage area of the earth surface for the MEO 1 satellite (SPIRALE B) with altitude of 14758.66 km is 27.55 % while that of HEO 5 satellite (TESS) with altitude of 236,454.93 km is 48.69 %. The results also show that at zero elevation angle, the coverage area tends to 50% as the orbital altitude increases.

The results of the horizon plane computations for the MEO, GEO and HEO case study satellites are presented in Figure 10, Figure 11 and Figure 12. The results show that the horizon plane increases with increase in orbital altitude. Specifically, the horizon plane for the MEO 1 satellite (SPIRALE B) with altitude of 14758.66 km is 25378.79 km while that of HEO 5 satellite (TESS) with altitude of 236,454.93 km is 485506.32 km. Again, the results of the coverage area, horizon plan and orbital altitude normalized with respect to MEO 1 show that the coverage area of HEO 5 satellite (TESS) is 1.8 times that of MEO 1, the horizon plane of HEO 5 satellite (TESS) is 19.1 times that of MEO 1, and the orbital altitude of HEO 5 satellite (TESS) is 30.2 times that of MEO 1. In Essence, the increase in orbital altitude is higher than the increase in both coverage area and horizon plane.

Table 5 The results of the coverage area (%) versus elevation computations for the MEO, GEO and HEO case study satellites

Elevation angle (°)	Coverage Area (%) for MEO Satellite 1	Coverage Area (%) for MEO Satellite 3	Coverage Area (%) for MEO Satellite 5	Coverage Area (%) for GEO Satellite 1	Coverage Area (%) for GEO Satellite 2	Coverage Area (%) for HEO Satellite 1	Coverage Area (%) for HEO Satellite 3	Coverage Area (%) for HEO Satellite 5
0	27.55	38.02	41.02	42.18	42.44	42.58	46.74	48.69
2.5	25.64	35.93	38.89	40.04	40.30	40.44	44.57	46.51
5	23.82	33.88	36.80	37.93	38.19	38.33	42.41	44.34
7.5	22.09	31.89	34.75	35.87	36.11	36.25	40.28	42.19
10	20.44	29.95	32.74	33.84	34.08	34.22	38.17	40.05
12.5	18.87	28.06	30.78	31.85	32.09	32.22	36.09	37.93
15	17.39	26.24	28.87	29.91	30.14	30.27	34.04	35.84
17.5	15.99	24.47	27.02	28.02	28.24	28.37	32.03	33.78
20	14.67	22.76	25.21	26.18	26.39	26.52	30.05	31.74
22.5	13.43	21.12	23.46	24.39	24.60	24.71	28.12	29.75
25	12.26	19.54	21.77	22.66	22.86	22.97	26.23	27.80
27.5	11.16	18.02	20.14	20.98	21.17	21.28	24.38	25.89
30	10.13	16.56	18.57	19.37	19.54	19.64	22.59	24.02
32.5	9.17	15.17	17.05	17.81	17.98	18.07	20.85	22.21
35	8.27	13.84	15.61	16.31	16.47	16.56	19.17	20.45
37.5	7.43	12.58	14.22	14.88	15.02	15.10	17.55	18.74

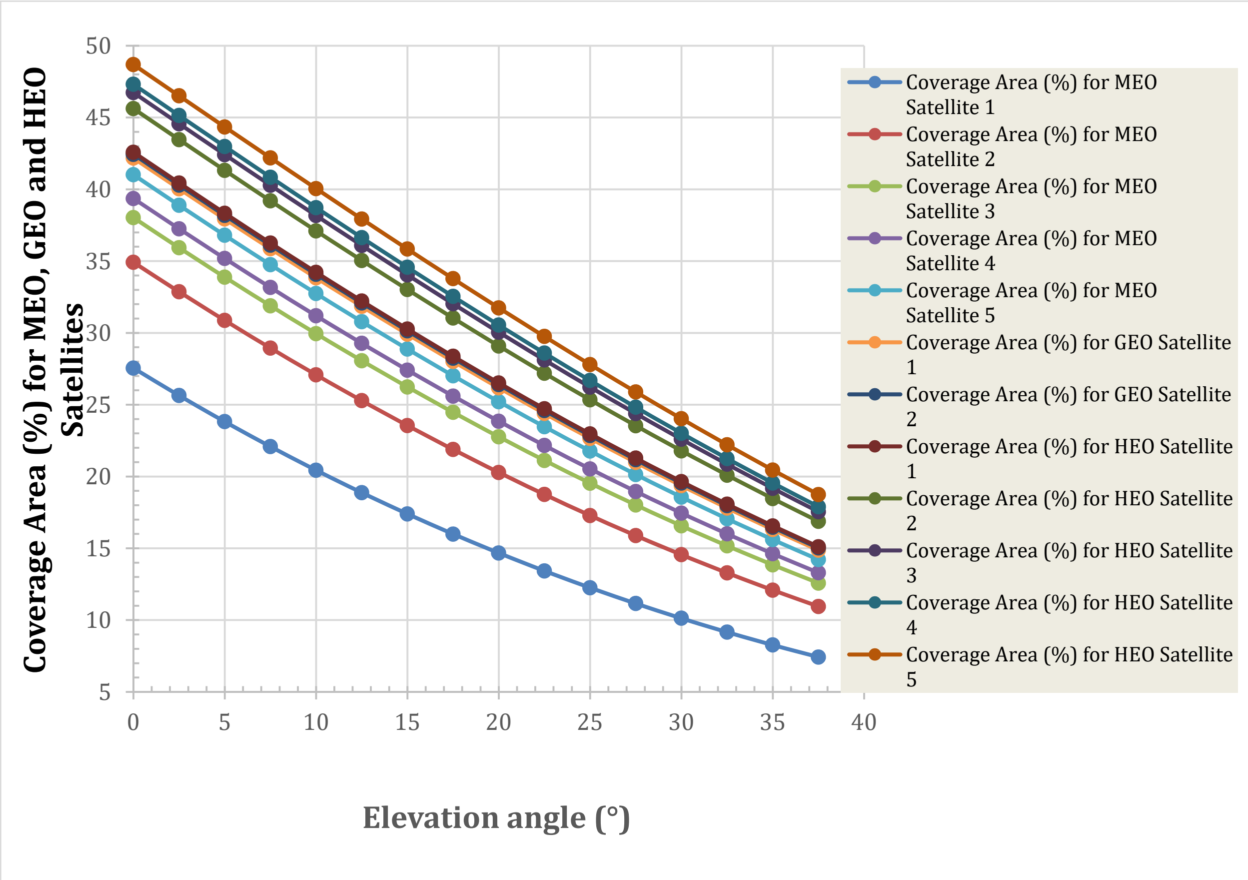


Figure 8 The coverage area (%) versus elevation graph for the MEO, GEO and HEO case study satellites

Table 6 The results of the coverage area (%) versus orbital altitude computations for the MEO, GEO and HEO case study satellites

Orbital Altitude, Hs (km)	Coverage Arear (%) for Elevation Angle, El =0°	Coverage Arear (%) for Elevation Angle, El =5°	Coverage Arear (%) for Elevation Angle, El =10°
7824.1	27.55	23.82	20.44
14758.66	34.91	30.87	27.08
20248.23	38.02	33.88	29.95
23590.43	39.36	35.18	31.19
29112.69	41.02	36.80	32.74
34395.48	42.18	37.93	33.84
35784.82	42.44	38.19	34.08
36606.86	42.58	38.33	34.22
66455.65	45.62	41.31	37.10
91325.32	46.74	42.41	38.17
112177.53	47.31	42.98	38.72
236458.93	48.69	44.34	40.05

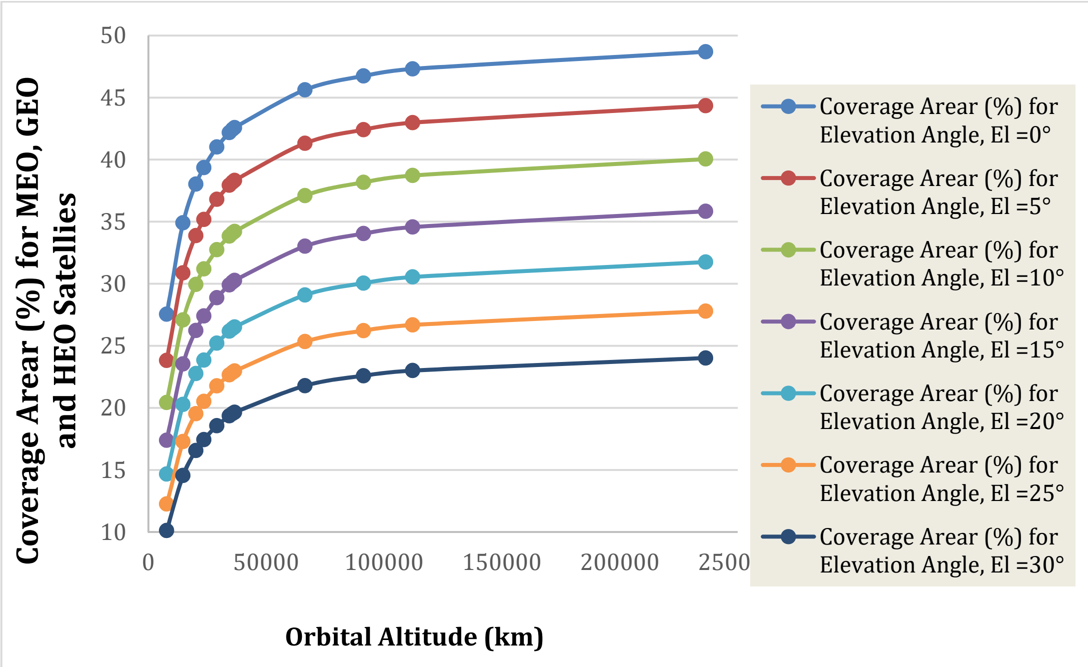
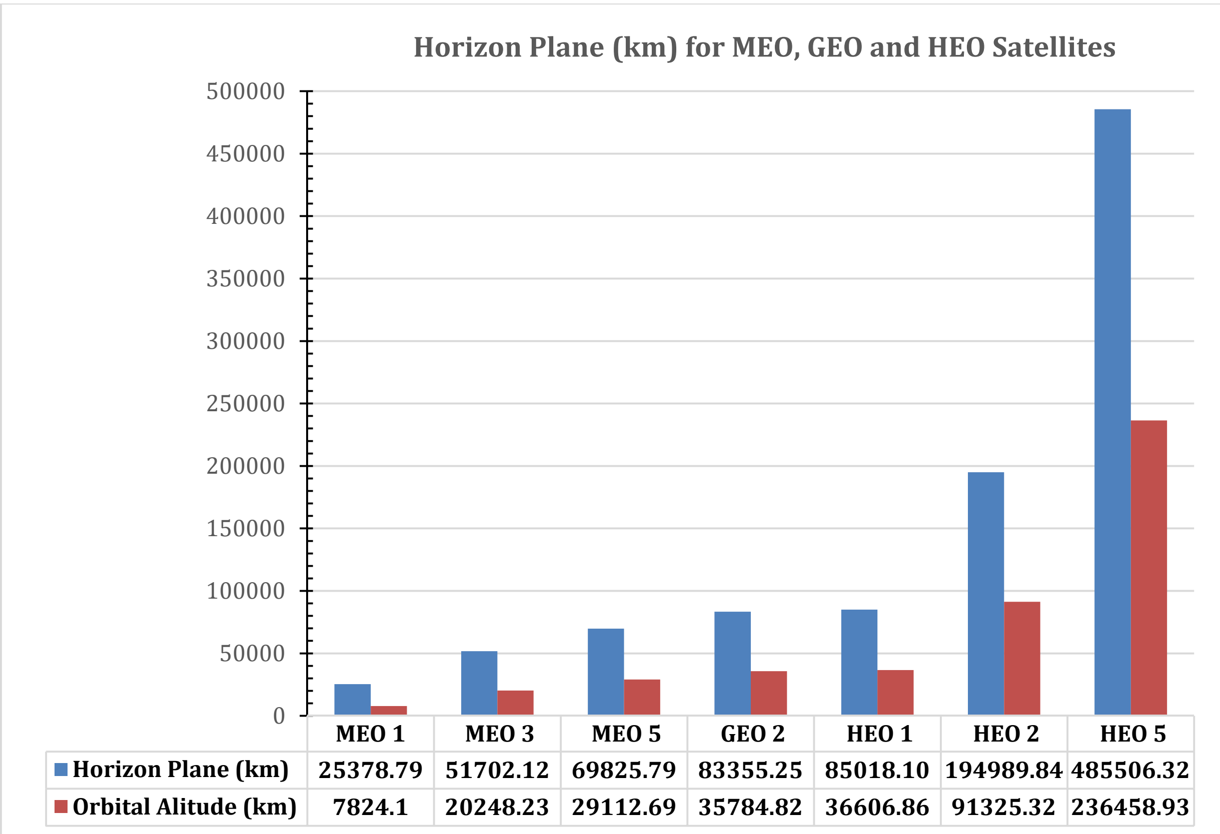


Figure 9 The coverage area (%) versus orbital altitude for the MEO, GEO and HEO case study satellites



	MEO 1	MEO 3	MEO 5	GEO 2	HEO 1	HEO 2	HEO 5
Horizon Plane (km)	25378.79	51702.12	69825.79	83355.25	85018.10	194989.84	485506.32
Orbital Alitude (km)	7824.1	20248.23	29112.69	35784.82	36606.86	91325.32	236458.93

Figure 10 The bar chart of the horizon plane for the MEO, GEO and HEO case study satellites

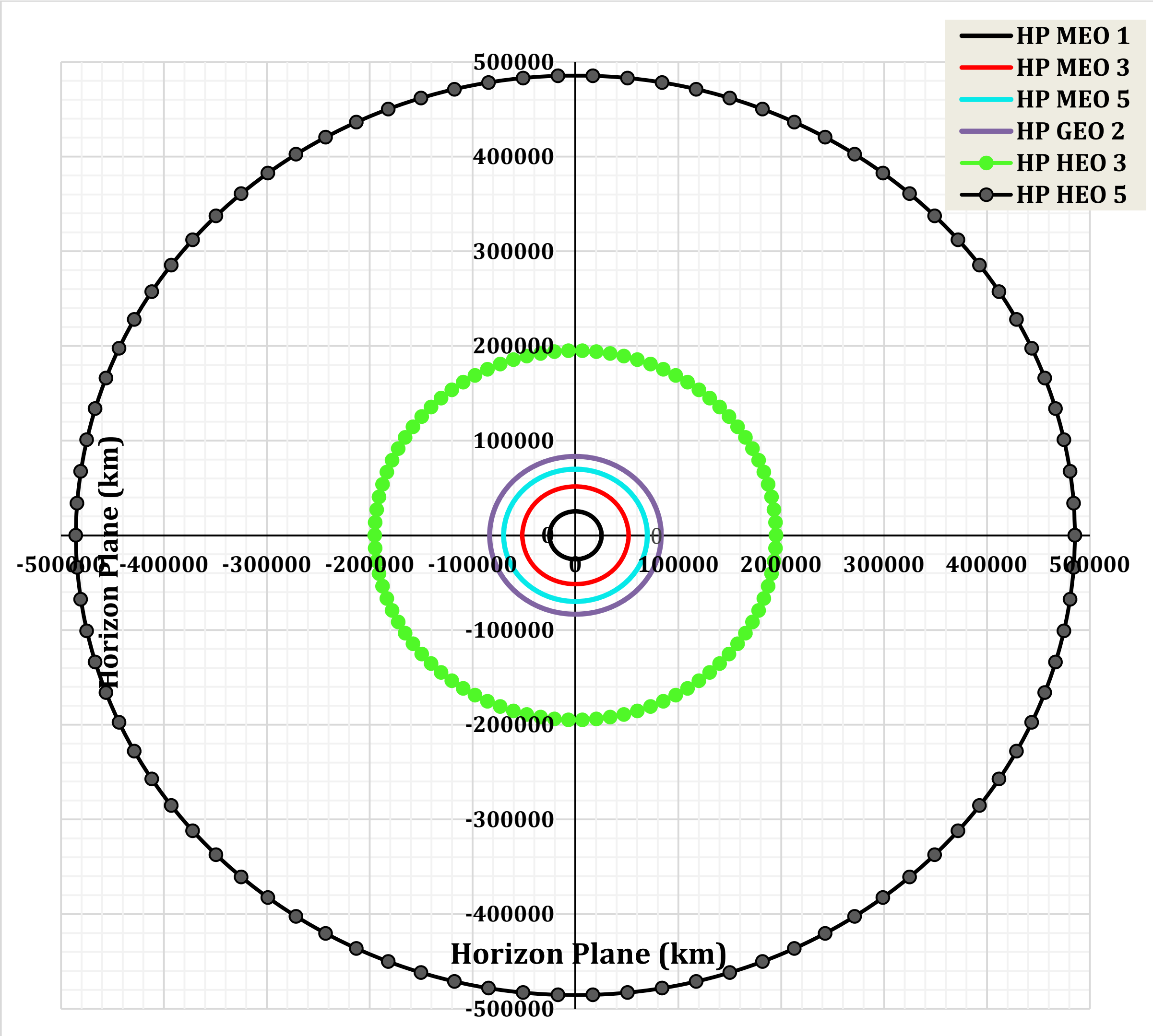
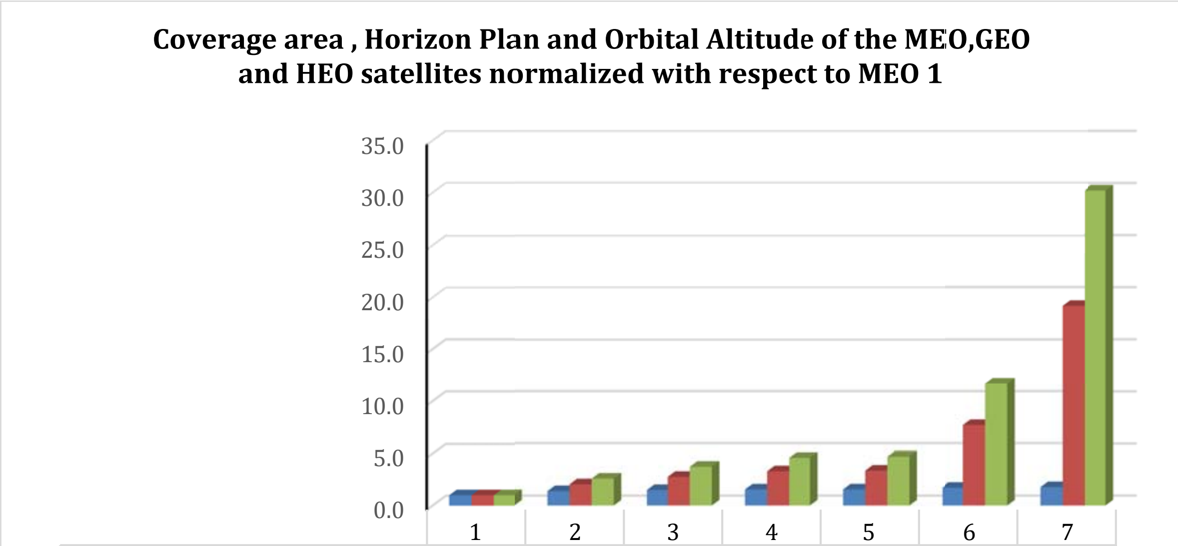


Figure 11 The radial plot of the horizon plane for the MEO, GEO and HEO case study satellites



	1	2	3	4	5	6	7
Coverage Area (%) normalized with respect to MEO 1 (%)	1.0	1.4	1.5	1.5	1.5	1.7	1.8
Horizon Plane normalized with respect to MEO 1	1.0	2.0	2.8	3.3	3.3	7.7	19.1
Orbital Altitude normalized with respect to MEO 1	1.0	2.6	3.7	4.6	4.7	11.7	30.2

Figure 12 The Coverage area, Horizon Plan and Orbital Altitude of the MEO,GEO and HEO satellites normalized with respect to MEO 1

4. Conclusion

Analysis of the area of the earth surface covered by earth orbiting satellites is presented. Also, the analysis of the horizon plane of the satellites are studied. Eighteen case study satellites were selected from the LEO, MEO, GEO and HEO orbit categories. The focus of the study is on the variation of coverage area and horizon plane of satellites with respect to their orbital altitude and elevation angles.

In all, it was found that the maximum coverage area occur at elevation angle of zero degree (0^o) and the rate of increase in orbital altitude is higher than the rate of increase in coverage area. Again, the rate of increase in horizon plane is lower than the rate of increase in the of coverage area. Also, at high altitude, in the case of HEO satellites, the coverage area tends to 50%.

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