Journal of Multidisciplinary Engineering Science Studies (JMESS)
ISSN: 2458-925X
Vol. 8 Issue 6, June - 2022

Design And Application Of Parametric Analysis Program For Circular Orbit Satellite Visibility Time

Uduak Etim Udoka[1]

Department of Computer Engineering
Akwa Ibom State Polytechnic , Ikot Osurua Ikot Ekpene

Okon, Abasiama Colman[2]
Department of Computer Engineering
Akwa Ibom State Polytechnic , Ikot Osurua Ikot Ekpene

Ufot Okon Nsa[3]

Department of Computer Engineering
Akwa Ibom State Polytechnic , Ikot Osurua Ikot Ekpene

Abstract— **In this paper, the design and application of parametric analysis program for circular orbit satellite visibility time is presented. The focus was on those satellites with eccentricity of zero or eccentricity value that approximates to zero when rounded off to about one decimal place. The analytical expressions for the computation of the visibility time for circular orbit satellites are presented and the analytical expressions showed that the visibility time of such orbits depend mainly on the altitude of the satellite and the imposed minimum zenith angle restriction. Then program is designed in this paper for evaluating the effect of those two key parameters on the visibility time of circular orbit satellites. Sample numerical examples are presented using four different satellites, namely, USA 215 satellite drawn from the LEO (low earth orbit) category, GALILEO-FM4 satellite drawn from the MEO (medium earth orbit) category, MEASAT 2 satellite drawn from the GEO (geosynchronous earth orbit) category and CTDRS satellite drawn from the HEO (high earth orbit) category. The results showed that the visibility time increases with orbital altitude and tends to the value of the orbital period as the altitude increases. The results also showed that the USA 215 satellite with the lowest altitude among the four satellites had the lowest visibility time and the lowest percentage of visibility time to orbital period while the CTDRS satellite with the highest altitude among the four satellites had the highest visibility time and the highest percentage of visibility time to orbital period. In essence, the visibility time as well as the percentage of visibility time to orbital period increase with orbital attitude. The program presented in this paper is useful parametric analysis of satellite visibility time when the orbit is circular or the eccentricity is approximately zero.**

Keywords— Parametric Analysis, Computer Program Design, Circular Orbit, Eccentricity, Satellite Visibility Time

1. Introduction

Today, there are numerous earth orbiting satellites that are categorised in many different ways based on their applications, their altitude, their orbital shape or eccentricity, their orbital inclination angle, their relationship with earth rotation, and based on some other parameters [1,2, 3,4, 5,6, 7,8, 9,10, 11,12, 13,14, 15,16]. In all these satellites, their usefulness to the earth station or for applications on earth is based on the fact that these satellites can be accessed from certain locations on the earth. The amount of time that these satellites are accessible on earth is referred to as their visibility time and it is usually a fraction or percentage of the orbital period of the satellite [17,18,19,20,21,22,23,24,25,26,27,28]. Accurate estimation of the satellite visibility time is essential in the design of satellite constellations and in scheduling some functions in satellite-based applications and systems [29,30,31,32,33,34,35].

Importantly, it has been noted that in practice, no single satellite can cover the whole earth at a time or no single satellite can be visible all over the earth at a time [36,37,38,39]. Accordingly, satellites are usually deployed as constellations where more than one satellites are deployed as a set of satellites that are coordinated together to ensure global visibility and application of the satellite functionalities [40,41,42,43,44,45,46,47]. Notably, most of the earth orbiting satellites are have circular or near circle orbits with eccentricity values that are approximately equal to zero. The visibility time of such satellites are dependent on mainly the orbital altitude and the minimum zenith angle restriction. The visibility time varies with the altitude and the zenith angles of many of the satellites vary with the orbital motions of the satellites. In this paper, a program is designed for computing the visibility time for earth orbiting satellites with circular orbits. The program applicability is also demonstrated using some sample case study numerical computations.

2. Methodology

2.1 The Analytical Model for Satellite Visibility Time Computation for Circular Orbit

According to [49], the visibility time (Δt_v) in seconds for circular orbit satellite is defined with respect to the satellite's orbit altitude (h) in km and the minimum zenith angle restriction (θ) in radian and it is given as;

$$\Delta t_{vS} = \left(4\left(\mathrm{Tan}^{-1}\left(\frac{\sqrt{(1+Z^2-\rho^2)}-Z}{1+\rho}\right)\right)\right)\sqrt{\frac{(R_e+h)^3}{\mu}} \quad (1)$$

where

$$h = R_s - R_e \quad (2)$$

$$\rho = \frac{R_e}{R_e+h} \quad (3)$$

$$\varphi = \begin{cases} (\pi/2) - \theta & \text{if } \varphi \text{ and } \theta \text{ are in radians} \\ \varphi = 90 - \theta & \text{if } \varphi \text{ and } \theta \text{ are in degree} \end{cases} \quad (4)$$

$$Z = \frac{1}{\mathrm{Tan}(\varphi)} \quad (5)$$

Where R_e is the radius of the earth in km, R_s is the radius of the satellite orbit in km and $\mu = 398600 \text{ km}^3/s^2$. The visibility time in minutes (Δt_{vM}) and in hours (Δt_{vM}) are defined respectively as follows;

$$\Delta t_{vM} = \frac{\Delta t_{vS}}{60} \quad (6)$$

$$\Delta t_{vH} = \frac{\Delta t_{vS}}{3600} \quad (7)$$

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

Let RTV be the ratio of To in minutes to Δt_{vM} expressed in percentage, hence;

$$\mathrm{RTV} = \left(\frac{\Delta t_{vM}}{T_o}\right) 100\ \% \quad (9)$$

2.2 Design of the Pseudocode for Satellite Visibility Time Computation for Circular Orbit

In the parametric analysis the effect of variation in the value of the satellite's orbit altitude (h) on the satellite's visibility time is examined. Also, the parametric analysis considered the effect of variation in the value of the minimum zenith angle restriction (θ) on the satellite's visibility time.

The pseudocode based on C language is used to present the design of the program for parametric analysis of the visibility time of satellite as a function of (i) the satellite's orbit altitude (h and (ii) the minimum zenith angle restriction (θ). The two parametric analysis options are designed as two different functions, namely, (i) Function Compute_VTS_by_h ( ) for the analysis with respect to h and (ii) Function Compute_VTS _by_theta ( ) for the analysis with respect to θ. The main function uses the variable PA to choose between the two functions and then transfers control of the program to the chosen function which computes the visibility times and displays the values in a tabular form as follows;

The program consists of four different functions or subroutines, as follows;

i. Function main ()
   The main function that starts and ends the program and also call the second and third functions depending on the user's choice of parametric analysis type
ii. Function Compute_VTS_by_h ( )
   This function is used to perform the parametric analysis with respect to the satellite's orbit altitude (h). It computes the satellites visibility time for various values of h. Essentially, it is used to compare the visibility time of different satellites based on the orbital altitudes but with a constant Minimum zenith angle restriction (θ). In order to compute the visibility time for each of the satellite, this function will call the function compute_VT (θ , h) which duty is to compute visibility time in seconds given h and θ. The visibility time results obtained from the function compute_VT (θ , h) is then converted to time in minutes and in hours.
iii. Function Compute_VTS _by_theta ( )
   This function is used to perform the parametric analysis with respect to the minimum zenith angle restriction (θ). It computes the satellites visibility time for various values of θ. Essentially, it is used to compare the visibility time for the same satellite based on the same orbital altitudes but with different minimum zenith angle restriction (θ). In order to compute the visibility time for each of the minimum zenith angle restriction (θ), this function will call the function compute_VT (θ , h) which duty is to compute visibility time in seconds given h and θ . The visibility time results obtained from the function compute_VT (θ , h) is then converted to time in minutes and in hours.

Function compute_VT (θ , h)
   This function is used to compute the visibility time in seconds when the values of h and θ are given.

The details of the pseudocode with the four functions are presented as follows;

```
Function main ()
    Input Re   //in km
    Define μ = 398600  // in km³/s²
    Input PA // Select parametric analysis parameter type:
    '1' for h and '2' for θ
    If PA = 1 Then
        Call Function Compute_VTS_by_h
    Else
        Call Function  Compute_VTS _by_theta
    EndIf
   Return
End function main
Function Compute_VTS_by_h ( )
Input   Xmax   // input the number of different satellites
                  orbits radius, Rs (in km ) that will be
                  considered
Declare array   Rs[Xmax] // array Rs[Xmax] holds the
                           1,2,3,…Xmax orbital radius
Declare arrays  h[Xmax]   // array h[Xmax] holds the
                           1,2,3,…Xmax orbital altitude
Declare arrays  VTS[Xmax] // array VTS[Xmax] holds the
                           1,2,3,…Xmax visibility times
                           in seconds
```

Declare arrays VTM[Kmax] // array VTM[Kmax] holds the 1,2,3,… Kmax visibility times in minutes
Declare arrays VTH[Kmax] // array VTH[Kmax] holds the 1,2,3,… Kmax visibility times in hour
Declare arrays ToM[Kmax] // array Tom[Kmax] holds the 1,2,3,… Kmax orbital period in minute
Declare arrays RTVM [Kmax] // array RTVM [Kmax] holds the 1,2,3,… Kmax ratio of VTM[Kmax to Tom[Kmax expressed in percentage
Input θ // the minimum zenith angle restriction (θ) in radian
For x = 1 , x ≤ Xmax, x = x + 1
Input Rs[x]
$h[x]$= Rs[x] $- R_e$
VTS[x]= compute_VT (θ , $h[x]$) // Call the function to the xth visibility time in seconds given θ and $h[x]$

VTM[x] $= \frac{VTS[x]}{60}$
VTH[x] $= \frac{VTS[x]}{3600}$
ToM[x] $= 2\pi\sqrt{\frac{(\mathrm{Rs}[x])^3}{\mu}}$
RTVM [x] $= \left(\frac{\mathrm{VTM}[x]}{\mathrm{ToM}[x]}\right)100$
Output x, θ, $h[x]$, ToM[x], VTS[x], VTM[x] , VTH[x], RTVM [x]
Next For Loop
End For Loop
Return
End Function Compute_VTS_by_h

Function Compute_VTS _by_theta ( )
Input θmax // input the maximum value of the minimum zenith angle restriction (θ) in radian that will considered
Input Kmax // input the maximum number of subunits the range 0 to θmax will be divided
Declare array **θArr**[Kmax] // array **θArr**[Kmax] holds the 1,2,3,…Kmax minimum zenith angle restrictions
Declare arrays VTS[Kmax] // array VTS[Kmax] holds the 1,2,3,… Kmax visibility times in seconds
Declare arrays VTM[Kmax] // array VTM[Kmax] holds the 1,2,3,… Kmax visibility times in minutes
Declare arrays VTH[Kmax] // array VTH[Kmax] holds the 1,2,3,… Kmax visibility times in hour
Declare arrays ToM[Kmax] // array Tom[Kmax] holds the 1,2,3,… Kmax orbital period in minute
Declare arrays RTVM [Kmax] // array RTVM [Kmax] holds the 1,2,3,… Kmax ratio of VTM[Kmax to Tom[Kmax expressed in percentage
Input Rs // input the radius of the satellite orbit in km
$h = \mathrm{Rs} - R_e$
For k = 1 , k ≤ Kmax, k = k + 1
θArr[k] $= k\left(\frac{\theta\mathrm{max}}{\mathrm{Kma}}\right)$
VTS[k] = compute_VT (**θArr**[k] ,h) // Call the function to the kth visibility time in seconds given **h** and **θArr**[k]
VTM[k] $= \left(\frac{VTS[k]}{60}\right)$
VTH[k] $= \frac{VTS[k]}{3600}$
ToM[k] $= 2\pi\sqrt{\frac{(\mathrm{Rs})^3}{\mu}}$
RTVM[k] $= \left(\frac{\mathrm{VTM}[k]}{\mathrm{ToM}[k]}\right)100$
Output k, **θArr**[k], h , ToM[k] , VTS[k], VTM[k], VTH[k], RTVM[k]
Next For Loop
End For Loop
Return
End Function Compute_VTS _by_theta ( )

Function compute_VT (θ , h) //Function to compute visibility time in seconds given h and θ
Compute $\varphi = (\pi/2) - \theta$
Compute $Z = \frac{1}{\mathrm{Tan}(\varphi)}$
Compute $\rho = \frac{R_e}{R_e + h}$
Compute $VTS = \left(4\left(\mathrm{Tan}^{-1}\left(\frac{\sqrt{(1+Z^2-\rho^2)} - Z}{1+\rho}\right)\right)\right)\sqrt{\frac{(R_e+h)^3}{\mu}}$
Return VTS
End Function compute_VT

3. The case study circular orbit satellites

The case study circular orbit satellites are shown in Table 1 and the view of each of the case study satellite's orbit from above orbital plane, as accessed at https://www.heavens-above.com, are presented in Figure 1, Figure 2, Figure 3 and Figure 4. The four satellites are drawn from the LEO (low earth orbit), MEO (medium earth orbit), GEO (geosynchronous earth orbit), and HEO (high earth orbit), orbit categories.

Table 1 The details of the case study circular orbit satellites

Orbit Type	Satellite Name and Norad ID	Eccentricity	Semi major axis in km	Orbital Altitude in km	Source
I. LEO	II. USA 215 III. : 37162	0.0006249	7482	1104	https://www.n2yo.com/satellite/?s=33105
IV. MEO	V. GALILEO-FM4 VI. : 38858	0.0001226	29600	23222	https://www.n2yo.com/satellite/?s=38858
VII. GEO	III. MEASAT 2 :24653	0.0005718	42339	35961	https://www.n2yo.com/satellite/?s=44476
IX. HEO	X. CTDRS XI. :32779	0.0002067	42985	36607	https://www.n2yo.com/satellite/?s=32779

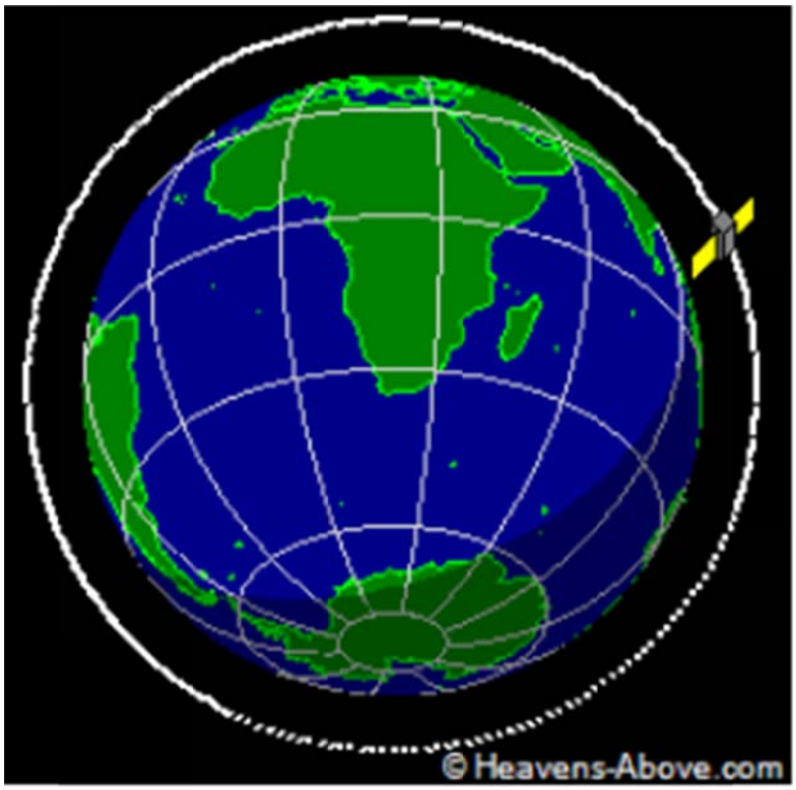

Figure 1 The view of USA 215 satellite from above orbital plane, accessed at https://www.heavens-above.com

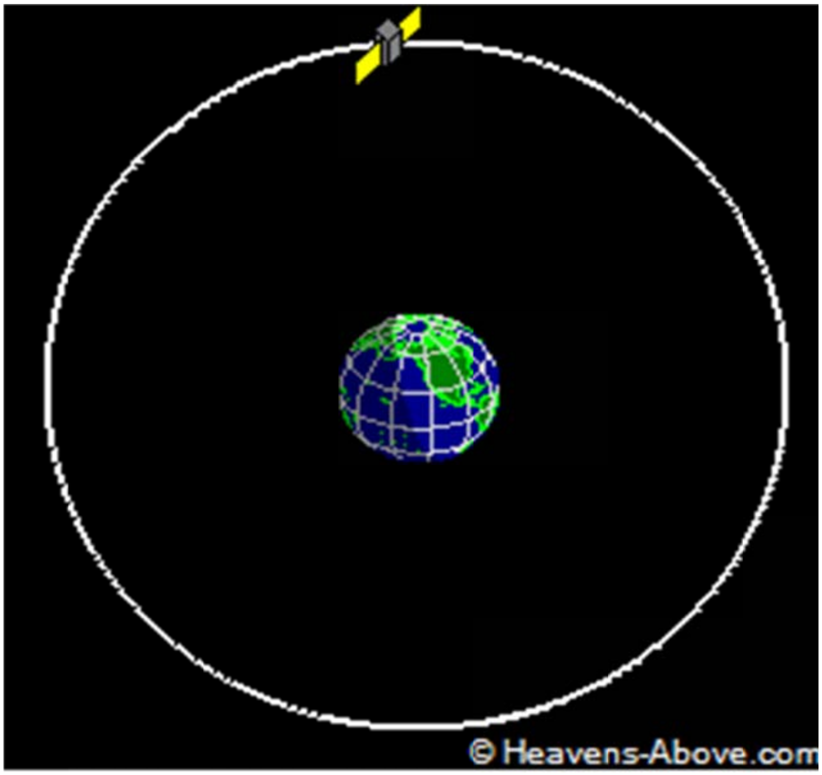

Figure 2 The view of GALILEO-FM4 satellite from above orbital plane, accessed at https://www.heavens-above.com

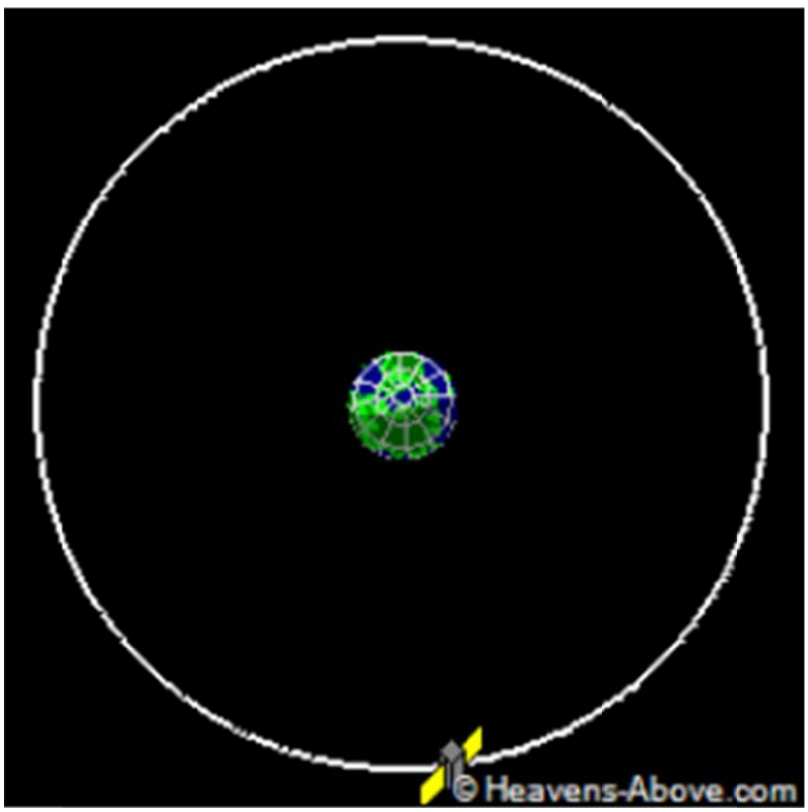

Figure 3 The view of Measat 2 satellite from above orbital plane, accessed at https://www.heavens-above.com

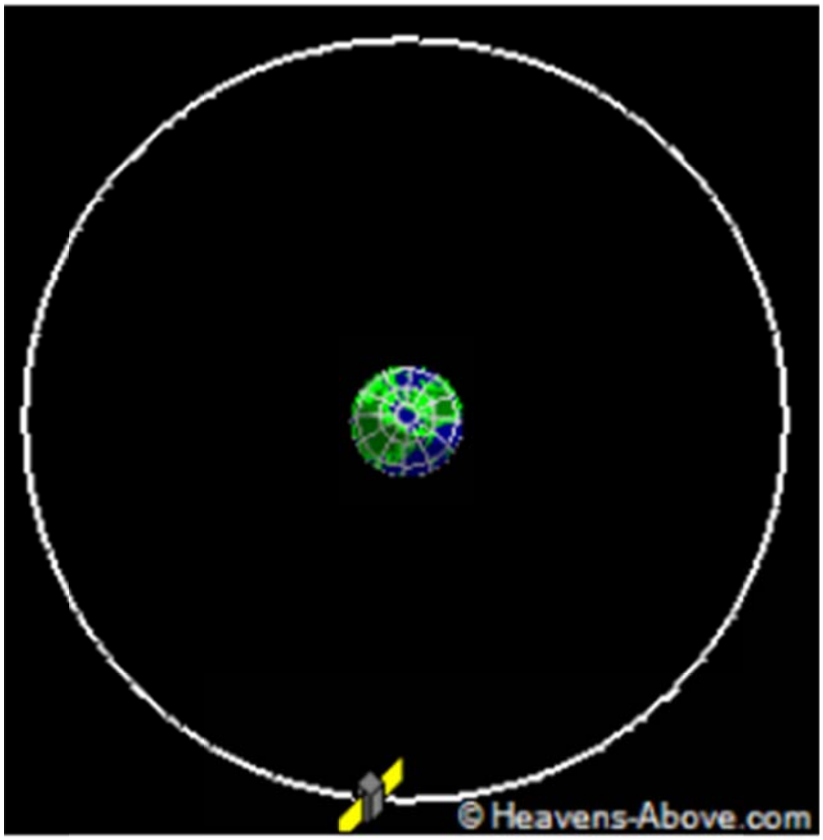

Figure 4 The view of CTDRS satellite from above orbital plane, accessed at https://www.heavens-above.com

3. Results and discussion

The program has two functions that are used for the actual computations in the parametric analysis, namely, Compute_VTS_by_h and Compute_VTS _by_theta. The output of the program with respect to the function Compute_VTS_by_h is shown in Table 2 where the orbital altitudes range is computed with the USA 215 satellite with semi major axis of 7482 km to CTDRS satellite with semi major axis of 42985 km, and the minimal zenith angle restriction, θ = 0 degree. Similar outputs from the program function for the case where minimal zenith angle restriction, θ = 5 degree is presented in Table 3 and for the case where minimal zenith angle restriction, θ = 10 degree is presented in Table 4. In addition, the visibility time in minutes versus orbital altitude in km for minimal zenith angle restriction, θ = 0° , θ =5° and θ =10°, as extracted from Table 2, Table 3 and Table 4 are plotted in Figure 5. Also, the percentage of visibility time to orbital period (%) versus orbital altitude in km for minimal zenith angle restriction, θ = 0° , θ =5° and θ =10° as extracted from Table 2, Table 3 and Table 4 are plotted in Figure 6. According to the results in Figure 5 and Figure 5, as well as in Table 2, Table 3 and Table 4, the visibility time increases with orbital altitude and tends to the value of the orbital period as the altitude increases. Also, the percentage of visibility time to orbital period (%) increases with orbital altitude and tends to 50 % as the altitude increases.

Table 2 The output of the program with respect to the function Compute_VTS_by_h where the orbital altitudes range is computed with the USA 215 satellite with semi major axis of 7482 km to CTDRS satellite with semi major axis of 42985 km, and the minimal zenith angle restriction, θ = 0 degree

Variables names in the program	k	θ[k] (°)	h[k] (km)	ToM[k] (Minutes)	VTS[k] (Second)	VTM[k] (Minutes)	VTH[k] (Hours)	RTVM[k] %
Satellite	S/N	Minimal Zenith Angle Restriction, θ (degree)	Orbital altitude, h (km)	Orbital Period , To (Min)	Visibility Time, Δtvs (Sec)	Visibility Time, Δtvm (Min)	Visibility Time, Δtvh (Hour)	Percentage of visibility time to orbital period (%)
USA 215	1	0.0	1104.0	107.35	1127.90	18.80	0.31	17.51
	2	0.0	4654.0	192.19	3503.09	58.38	0.97	30.38
	3	0.0	8205.0	292.10	6237.72	103.96	1.73	35.59
	4	0.0	11755.0	405.01	9370.05	156.17	2.60	38.56
	5	0.0	15305.0	529.59	12867.82	214.46	3.57	40.50
GALILEO-FM4	6	0.0	23222.0	844.69	21837.00	363.95	6.07	43.09
	7	0.0	22406.0	810.00	20843.40	347.39	5.79	42.89
	8	0.0	25956.0	964.37	25274.17	421.24	7.02	43.68
MEASAT 2	9	0.0	35961.0	1445.00	39176.68	652.94	10.88	45.19
	10	0.0	33057.0	1298.91	34937.30	582.29	9.70	44.83
CTDRS	11	0.0	36607.0	1478.19	40141.25	669.02	11.15	45.26

Table 3 The output of the program with respect to the function Compute_VTS_by_h where the orbital altitudes range is computed with the USA 215 satellite with semi major axis of 7482 km to CTDRS satellite with semi major axis of 42985 km, and the minimal zenith angle restriction, θ = 5 degree

Variables names in the program	k	θ[k] (°)	h[k] (km)	ToM[k] (Minutes)	VTS[k] (Second)	VTM[k] (Minutes)	VTH[k] (Hours)	RTVM[k] %
Satellite	S/N	Minimal Zenith Angle Restriction, θ (degree)	Orbital altitude, h (km)	Orbital Period , To (Min)	Visibility Time, Δtvs (Sec)	Visibility Time, Δtvm (Min)	Visibility Time, Δtvh (Hour)	Percentage of visibility time to orbital period (%)
USA 215	1	5.0	1104.0	107.35	961.64	16.03	0.27	14.93
	2	5.0	4654.0	192.19	3192.66	53.21	0.89	27.69
	3	5.0	8205.0	292.10	5761.22	96.02	1.60	32.87
	4	5.0	11755.0	405.01	8706.13	145.10	2.42	35.83
	5	5.0	15305.0	529.59	11997.08	199.95	3.33	37.76
GALILEO-FM4	6	5.0	23222.0	844.69	20442.87	340.71	5.68	40.34
	7	5.0	22406.0	810.00	19506.93	325.12	5.42	40.14
	8	5.0	25956.0	964.38	23681.19	394.69	6.58	40.93
MEASAT 2	9	5.0	35961.0	1445.01	36784.72	613.08	10.22	42.43
	10	5.0	33057.0	1298.92	32788.29	546.47	9.11	42.07
CTDRS	11	5.0	36607.0	1478.21	37694.19	628.24	10.47	42.50

Table 4 The output of the program with respect to the function Compute_VTS_by_h where the orbital altitudes range is computed with the USA 215 satellite with semi major axis of 7482 km to CTDRS satellite with semi major axis of 42985 km, and the minimal zenith angle restriction, θ = 10 degree

Variables names in the program	k	θ[k] (°)	h[k] (km)	ToM[k] (Minutes)	VTS[k] (Second)	VTM[k] (Minutes)	VTH[k] (Hours)	RTVM[k] %
Satellite	S/N	Minimal Zenith Angle Restriction, θ (degree)	Orbital altitude, h (km)	Orbital Period , To (Min)	Visibility Time, Δtvs (Sec)	Visibility Time, Δtvm (Min)	Visibility Time, Δtvh (Hour)	Percentage of visibility time to orbital period (%)
USA 215	1	10.0	1104.0	107.35	819.88	13.66	0.23	12.73
	2	10.0	4654.0	192.19	2901.81	48.36	0.81	25.16
	3	10.0	8205.0	292.10	5305.21	88.42	1.47	30.27
	4	10.0	11755.0	405.01	8064.17	134.40	2.24	33.19
	5	10.0	15305.0	529.59	11149.84	185.83	3.10	35.09
GALILEO-FM4	6	10.0	23222.0	844.69	19075.56	317.93	5.30	37.64
	7	10.0	22406.0	810.00	18196.93	303.28	5.05	37.44
	8	10.0	25956.0	964.38	22116.07	368.60	6.14	38.22
MEASAT 2	9	10.0	35961.0	1445.01	34424.25	573.74	9.56	39.70
	10	10.0	33057.0	1298.92	30669.71	511.16	8.52	39.35
CTDRS	11	10.0	36607.0	1478.21	35278.74	587.98	9.80	39.78

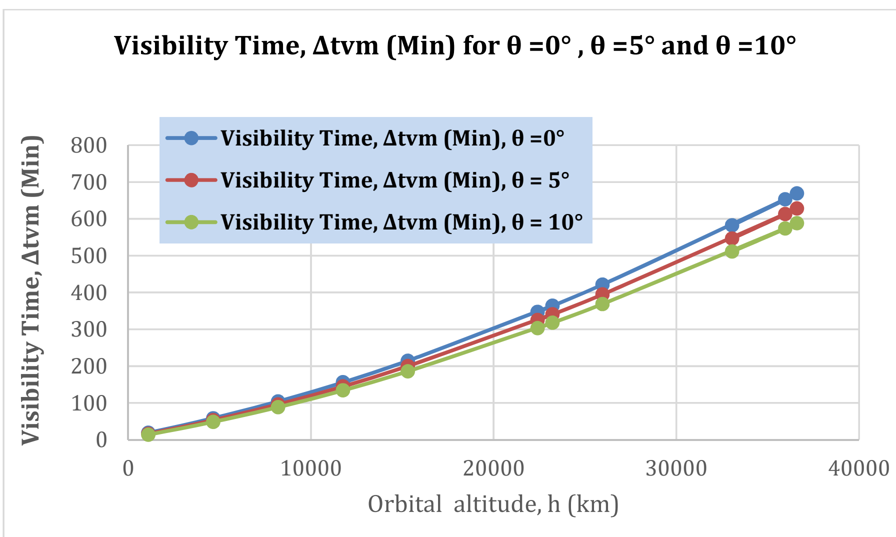

Figure 5 The Visibility Time in minutes versus orbital altitude in km for minimal zenith angle restriction, θ = 0° , θ =5° and θ =10°

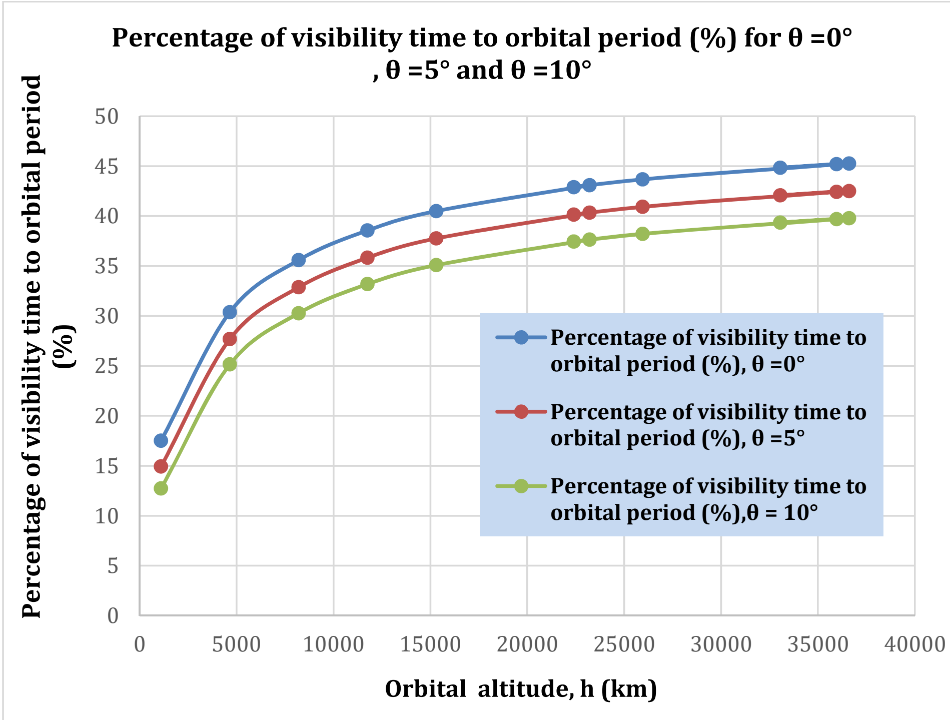

Figure 6 The percentage of visibility time to orbital period (%) versus orbital altitude in km for minimal zenith angle restriction, θ = 0° , θ =5° and θ =10°

The output of the program with respect to the function Compute_VTS _by_theta is shown in Table 5 for the USA 215 satellite, in Table 6 for the GALILEO-FM4 satellite, in Table 7 for the MEASAT 2 satellite, and in Table 8 for the CTDRS satellite. In each of the case study satellites, the Minimal Zenith Angle Restriction, θ (degree) was varied from 0 degree to 20 degrees in the steps of 2 degrees. In addition, the visibility time in minutes versus minimal zenith angle restriction, θ in degrees , as extracted from Table 5, Table 6, Table 7 and Table 8 for the fours case study satellites is plotted in Figure 7 while similar graph for the percentage of visibility time to orbital period (%) versus minimal zenith angle restriction, θ in degrees for the fours case study satellites is plotted in Figure 8. The results show that the USA 215 satellite with the lowest altitude (of 1104 km) among the four satellites has the lowest visibility time and the lowest percentage of visibility time to orbital period while the CTDRS satellite with the highest altitude (of 36607 km) among the four satellites has the highest visibility time and the highest percentage of visibility time to orbital period. In essence, the visibility time as well as the percentage of visibility time to orbital period increase with orbital attitude. Also, the results in Table 5, Table 6, Table 7 and Table 8 , as well as in Figure 6 and Figure 7 show that the visibility time and the percentage of visibility time to orbital period decrease as the minimal zenith angle restriction increases.

Table 5 The output of the program for the USA 215 satellite with respect to the function Compute_VTS _by_theta, the minimal zenith angle restriction, θ (degree)

Variables names in the program	k	θ[k] (°)	h[k] (km)	ToM[k] (Minutes)	VTS[k] (Second)	VTM[k] (Minutes)	VTH[k] (Hours)	RTVM[k] %
Satellite	S/N	Minimal Zenith Angle Restriction, θ (degree)	Orbital altitude, h (km)	Orbital Period , To (Min)	Visibility Time, Δtvs (Sec)	Visibility Time, Δtvm (Min)	Visibility Time, Δtvh (Hour)	Percentage of visibility time to orbital period (%)
USA 215	1	0.0	1104.0	107.35	1127.90	18.80	0.31	17.51
USA 215	2	2.0	1104.0	107.35	1058.37	17.64	0.29	16.43
USA 215	3	4.0	1104.0	107.35	992.88	16.55	0.28	15.42
USA 215	4	6.0	1104.0	107.35	931.38	15.52	0.26	14.46
USA 215	5	8.0	1104.0	107.35	873.76	14.56	0.24	13.57
USA 215	6	10.0	1104.0	107.35	819.87	13.66	0.23	12.73
USA 215	7	12.0	1104.0	107.35	769.56	12.83	0.21	11.95
USA 215	8	14.0	1104.0	107.35	722.63	12.04	0.20	11.22
USA 215	9	16.0	1104.0	107.35	678.88	11.31	0.19	10.54
USA 215	10	18.0	1104.0	107.34	638.10	10.64	0.18	9.91
USA 215	11	20.0	1104.0	107.34	600.08	10.00	0.17	9.32

Table 6 The output of the program for the GALILEO-FM4 satellite with respect to the function Compute_VTS _by_theta, the minimal zenith angle restriction, θ (degree)

Variables names in the program	k	θ[k] (°)	h[k] (km)	ToM[k] (Minutes)	VTS[k] (Second)	VTM[k] (Minutes)	VTH[k] (Hours)	RTVM[k] %
Satellite	S/N	Minimal Zenith Angle Restriction, θ (degree)	Orbital altitude, h (km)	Orbital Period , To (Min)	Visibility Time, Δtvs (Sec)	Visibility Time, Δtvm (Min)	Visibility Time, Δtvh (Hour)	Percentage of visibility time to orbital period (%)
GALILEO-FM4	1	0.0	23222.0	844.69	21837.14	363.95	6.07	43.09
GALILEO-FM4	2	2.0	23222.0	844.69	21276.18	354.60	5.91	41.98
GALILEO-FM4	3	4.0	23222.0	844.69	20719.56	345.33	5.76	40.88
GALILEO-FM4	4	6.0	23222.0	844.69	20167.26	336.12	5.60	39.79
GALILEO-FM4	5	8.0	23222.0	844.69	19619.27	326.99	5.45	38.71
GALILEO-FM4	6	10.0	23222.0	844.69	19075.56	317.93	5.30	37.64
GALILEO-FM4	7	12.0	23222.0	844.69	18536.12	308.94	5.15	36.57
GALILEO-FM4	8	14.0	23222.0	844.69	18000.91	300.02	5.00	35.52
GALILEO-FM4	9	16.0	23222.0	844.69	17469.89	291.16	4.85	34.47
GALILEO-FM4	10	18.0	23222.0	844.69	16943.02	282.38	4.71	33.43
GALILEO-FM4	11	20.0	23222.0	844.69	16420.24	273.67	4.56	32.40

Table 7 The output of the program for the MEASAT 2 satellite with respect to the function Compute_VTS _by_theta, the minimal zenith angle restriction, θ (degree)

Variables names in the program	k	θ[k] (°)	h[k] (km)	ToM[k] (Minutes)	VTS[k] (Second)	VTM[k] (Minutes)	VTH[k] (Hours)	RTVM[k] %
Satellite	S/N	Minimal Zenith Angle Restriction, θ (degree)	Orbital altitude, h (km)	Orbital Period , To (Min)	Visibility Time, Δtvs (Sec)	Visibility Time, Δtvm (Min)	Visibility Time, Δtvh (Hour)	Percentage of visibility time to orbital period (%)
MEASAT 2	1	0.0	35961.0	1445.01	39177.07	652.95	10.88	45.19
MEASAT 2	2	2.0	35961.0	1445.01	38216.29	636.94	10.62	44.08
MEASAT 2	3	4.0	35961.0	1445.01	37260.63	621.01	10.35	42.98
MEASAT 2	4	6.0	35961.0	1445.01	36310.08	605.17	10.09	41.88
MEASAT 2	5	8.0	35961.0	1445.01	35364.63	589.41	9.82	40.79
MEASAT 2	6	10.0	35961.0	1445.01	34424.25	573.74	9.56	39.70
MEASAT 2	7	12.0	35961.0	1445.01	33488.90	558.15	9.30	38.63
MEASAT 2	8	14.0	35961.0	1445.01	32558.56	542.64	9.04	37.55
MEASAT 2	9	16.0	35961.0	1445.01	31633.18	527.22	8.79	36.49
MEASAT 2	10	18.0	35961.0	1445.01	30712.72	511.88	8.53	35.42
MEASAT 2	11	20.0	35961.0	1445.01	29797.11	496.62	8.28	34.37

Table 8 The output of the program for the CTDRS satellite with respect to the function Compute_VTS _by_theta, the minimal zenith angle restriction, θ (degree)

Variables names in the program	k	θ[k] (°)	h[k] (km)	ToM[k] (Minutes)	VTS[k] (Second)	VTM[k] (Minutes)	VTH[k] (Hours)	RTVM[k] %
Satellite	S/N	Minimal Zenith Angle Restriction, θ (degree)	Orbital altitude, h (km)	Orbital Period , To (Min)	Visibility Time, Δtvs (Sec)	Visibility Time, Δtvm (Min)	Visibility Time, Δtvh (Hour)	Percentage of visibility time to orbital period (%)
CTDRS	1	0.0	36607.0	1478.21	40141.75	669.03	11.15	45.26
CTDRS	2	2.0	36607.0	1478.21	39158.86	652.65	10.88	44.15
CTDRS	3	4.0	36607.0	1478.21	38181.13	636.35	10.61	43.05
CTDRS	4	6.0	36607.0	1478.21	37208.54	620.14	10.34	41.95
CTDRS	5	8.0	36607.0	1478.21	36241.09	604.02	10.07	40.86
CTDRS	6	10.0	36607.0	1478.21	35278.74	587.98	9.80	39.78
CTDRS	7	12.0	36607.0	1478.21	34321.47	572.02	9.53	38.70
CTDRS	8	14.0	36607.0	1478.21	33369.23	556.15	9.27	37.62
CTDRS	9	16.0	36607.0	1478.21	32422.00	540.37	9.01	36.56
CTDRS	10	18.0	36607.0	1478.21	31479.71	524.66	8.74	35.49
CTDRS	11	20.0	36607.0	1478.21	30542.32	509.04	8.48	34.44

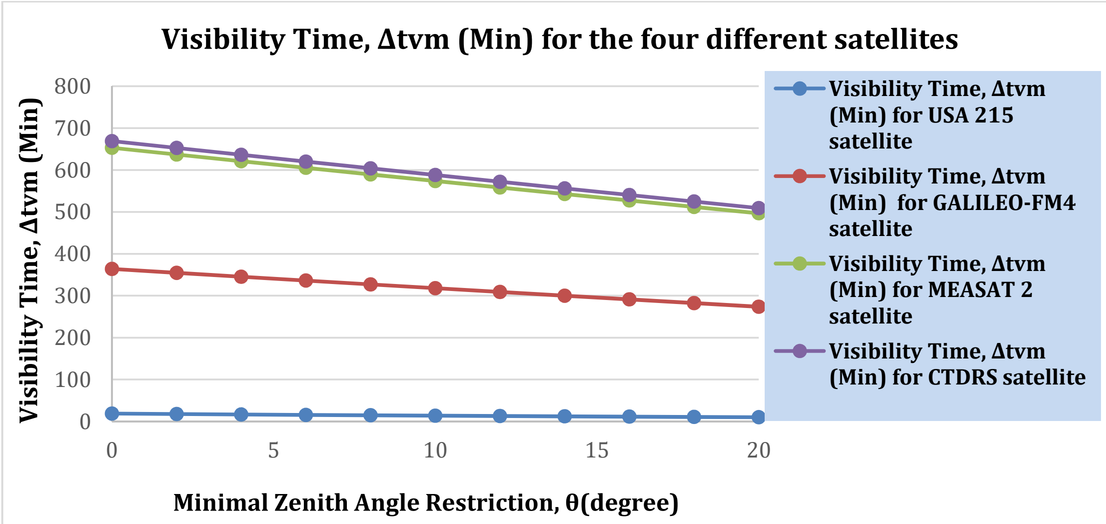

Figure 7 The Visibility Time in minutes versus minimal zenith angle restriction, θ in degrees for the fours case study satellites

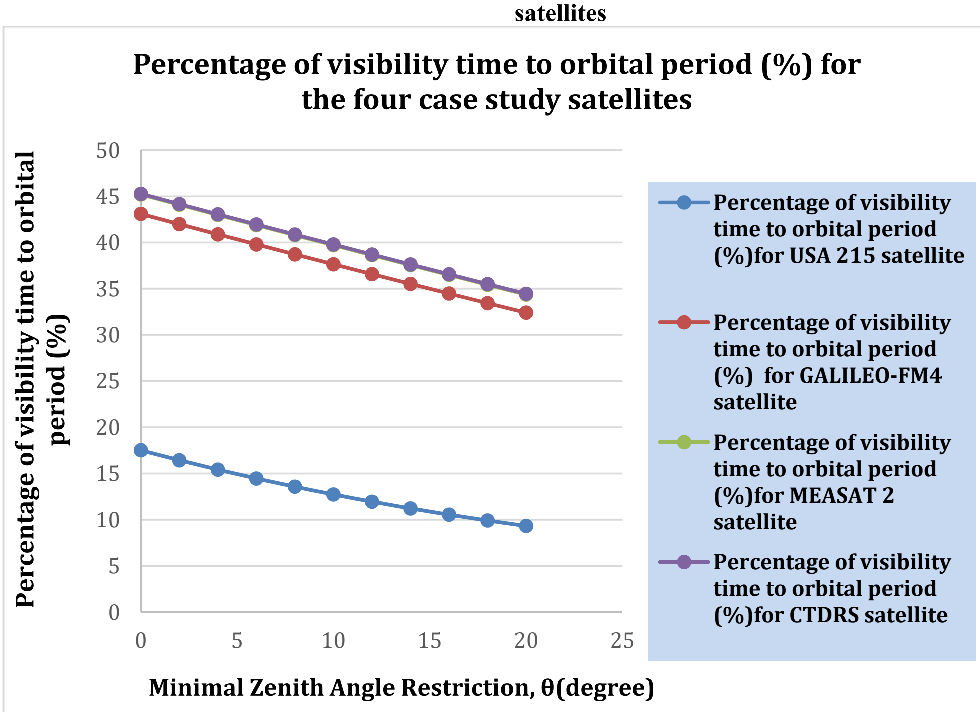

Figure 8 The percentage of visibility time to orbital period (%) versus minimal zenith angle restriction, θ in degrees for the fours case study satellites

4. Conclusion

The design and application of a parametric analysis program for evaluating the visibility time of circular orbit satellites is presented. The program enables the computation of the visibility time for satellites with eccentricity of zero or eccentricity value that approximates to zero when rounded off to about one decimal place. The analytical expressions for the visibility time of satellites with such orbits show that the visibility time depends mainly on the altitude of the satellite and the imposed minimum zenith angle restriction. The program presented in this paper is used to evaluate the effect of those two key parameters on the visibility time of satellites with circular orbit. Sample numerical examples are presented using four different satellites drawn from the LEO, MEO, GEO and HEO orbit categories.

References

1. Capderou, M. (2014). *Handbook of satellite orbits: From kepler to GPS*. Springer Science & Business.
2. Zhu, L., Suomalainen, J., Liu, J., Hyyppä, J., Kaartinen, H., & Haggren, H. (2018). A review: Remote sensing sensors. *Multi-purposeful application of geospatial data*, 19-42.
3. Kramer, H. J., & Cracknell, A. P. (2008). An overview of small satellites in remote sensing. *International journal of remote Sensing*, *29*(15), 4285-4337.
4. Bourgoin, J. P., Meyer-Scott, E., Higgins, B. L., Helou, B., Erven, C., Huebel, H., ... & Jennewein,

T. (2013). A comprehensive design and performance analysis of low Earth orbit satellite quantum communication. *New Journal of Physics*, *15*(2), 023006.

5. Malik, J. S., & Bhatti, U. I. (2015, September). Remote sensing of ocean, ice and land surfaces using bistatically reflected GNSS signals from low Earth orbit. In *2015 Fourth International Conference on Aerospace Science and Engineering (ICASE)* (pp. 1-6). IEEE.
6. Del Portillo, I., Cameron, B. G., & Crawley, E. F. (2019). A technical comparison of three low earth orbit satellite constellation systems to provide global broadband. *Acta astronautica*, *159*, 123-135.
7. Sweeting, M. (2018). Modern small satellites-changing the economics of space. *Proceedings of the IEEE*, *106*(3), 343-361.
8. Maral, G., de Ridder, J. J., Evans, B. G., & Richharia, M. (1991). Low earth orbit satellite systems for communications. *International Journal of satellite communications*, *9*(4), 209-225.
9. Lemmens, S., & Krag, H. (2014). Two-line-elements-based maneuver detection methods for satellites in low earth orbit. *Journal of Guidance, Control, and Dynamics*, *37*(3), 860-868.
10. Cottin, H., Kotler, J. M., Billi, D., Cockell, C., Demets, R., Ehrenfreund, P., ... & Klamm, B. A. (2017). Space as a tool for astrobiology: review and recommendations for experimentations in Earth orbit and beyond. *Space Science Reviews*, *209*(1), 83-181.
11. Blackwell, W. J., Braun, S., Bennartz, R., Velden, C., DeMaria, M., Atlas, R., ... & Leslie, R. V. (2018). An overview of the TROPICS NASA earth venture mission. *Quarterly Journal of the Royal Meteorological Society*, *144*, 16-26.
12. Bentoutou, Y. (2012). A real time EDAC system for applications onboard earth observation small satellites. *IEEE Transactions on Aerospace and Electronic Systems*, *48*(1), 648-657.
13. Goldberg, M. D., Kilcoyne, H., Cikanek, H., & Mehta, A. (2013). Joint Polar Satellite System: The United States next generation civilian polar-orbiting environmental satellite system. *Journal of Geophysical Research: Atmospheres*, *118*(24), 13-463.
14. Liao, S. K., Cai, W. Q., Handsteiner, J., Liu, B., Yin, J., Zhang, L., ... & Pan, J. W. (2018). Satellite-relayed intercontinental quantum network. *Physical review letters*, *120*(3), 030501.
15. He, L., Ge, M., Wang, J., Wickert, J., & Schuh, H. (2013). Experimental study on the precise orbit determination of the BeiDou navigation satellite system. *Sensors*, *13*(3), 2911-2928.
16. Azami, H., Mosavi, M. R., & Sanei, S. (2013). Classification of GPS satellites using improved back propagation training algorithms. *Wireless personal communications*, *71*(2), 789-803.
17. Ali, I., Al-Dhahir, N., & Hershey, J. E. (1999). Predicting the visibility of LEO satellites. *IEEE Transactions on Aerospace and Electronic Systems*, *35*(4), 1183-1190.
18. Ali, I., Al-Dhahir, N., & Hershey, J. E. (1998). Doppler characterization for LEO satellites. *IEEE transactions on communications*, *46*(3), 309-313.
19. Ammar, M. K., Amin, M. R., & Hassan, M. H. M. (2018). Visibility intervals between two artificial satellites under the action of Earth oblateness. *Applied Mathematics and Nonlinear Sciences*, *3*(2), 353-374.
20. Tang, R., Yi, D., Zhu, J., Luo, Q., & Yao, J. (2007, July). TAIC algorithm for the visibility of the elliptical orbits' satellites. In *2007 IEEE International Geoscience and Remote Sensing Symposium* (pp. 781-785). IEEE.
21. Lee, J., Wang, S., Chung, D., Hyun, C., Choi, S., Ko, K., ... & Jung, O. (2013, March). Visibility conflict resolution for multiple antennae and multi-satellites via genetic algorithm. In *2013 IEEE Aerospace Conference* (pp. 1-10). IEEE.
22. Cox, T., & d'Antonio, P. (2016). *Acoustic absorbers and diffusers: theory, design and application*. Crc Press.
23. Reinhardt, A., & Neundorf, I. (2016). Design and application of antimicrobial peptide conjugates. *International journal of molecular sciences*, *17*(5), 701.
24. Chattha, K. S., Roth, J. A., & Saif, L. J. (2015). Strategies for design and application of enteric viral vaccines. *Annu Rev Anim Biosci*, *3*(1), 375-395.
25. Bhadra, S., & Ellington, A. D. (2014). Design and application of cotranscriptional non-enzymatic RNA circuits and signal transducers. *Nucleic acids research*, *42*(7), e58-e58.
26. Kang, C., Wang, S., Ren, W., Lu, Y., & Wang, B. (2019). Optimization design and application of active disturbance rejection controller based on intelligent algorithm. *Ieee Access*, *7*, 59862-59870.
27. Xing, L. (2018). Design and Application of a Fuzzy Evaluation Algorithm for Stroke Force in Calligraphy Teaching. *International Journal of Emerging Technologies in Learning*, *13*(7).
28. Park, K. T., Nam, Y. W., Lee, H. S., Im, S. J., Noh, S. D., Son, J. Y., & Kim, H. (2019). Design and implementation of a digital twin application for a connected micro smart factory. *International Journal of Computer Integrated Manufacturing*, *32*(6), 596-614.
29. Ulybyshev, Y. (2014). Geometric analysis and design method for discontinuous coverage satellite constellations. *Journal of Guidance, Control, and Dynamics*, *37*(2), 549-557.
30. Ortore, E., Cinelli, M., & Circi, C. (2017). A ground track-based approach to design satellite constellations. *Aerospace Science and Technology*, *69*, 458-464.
31. Paek, S. W., Kim, S., & de Weck, O. (2019). Optimization of reconfigurable satellite constellations using simulated annealing and genetic algorithm. *Sensors*, *19*(4), 765.
32. Liu, S., Li, P., Cui, G., & Wang, W. (2017, December). Design of satellite constellation with inter-satellite links for global communication using genetic algorithm. In *2017 20th International Symposium on Wireless Personal Multimedia Communications (WPMC)* (pp. 367-373). IEEE.

33. Casanova, D., Avendano, M. E., & Mortari, D. (2014). Design of flower constellations using necklaces. *IEEE Transactions on Aerospace and Electronic Systems*, *50*(2), 1347-1358.
34. Dai, C., Zheng, G., & Chen, Q. (2018). Satellite constellation design with multi-objective genetic algorithm for regional terrestrial satellite network. *China Communications*, *15*(8), 1-10.
35. Sarno, S., Graziano, M. D., & D'Errico, M. (2016). Polar constellations design for discontinuous coverage. *Acta Astronautica*, *127*, 367-374.
36. Pelton, J. N. (2017). Satellite Orbits for Communications Satellites. In *Handbook of Satellite Applications* (pp. 99-120). Springer, Cham.
37. Xu, A., Feng, X., Li, Y., Li, H., & He, D. (2019, January). Coverage of Hotspot Region with Small Satellite Constellation Design and Optimization. In *International Conference on Wireless and Satellite Systems* (pp. 109-119). Springer, Cham.
38. Washburn, A. R. (2004). Earth coverage by satellites in circular orbit. *Department of operations Research Naval Postgraduate School*.
39. Wilkinson, C. K. (1994). Coverage regions: how they are computed and used. *Journal of the Astronautical Sciences*, *42*(1), 47-70.
40. Crisp, N. H., Smith, K., & Hollingsworth, P. (2015). Launch and deployment of distributed small satellite systems. *Acta Astronautica*, *114*, 65-78.
41. Soret, B., & Smith, D. (2019, May). Autonomous routing for LEO satellite constellations with minimum use of inter-plane links. In *ICC 2019-2019 IEEE International Conference on Communications (ICC)* (pp. 1-6). IEEE.
42. Li, X., Ma, F., Li, X., Lv, H., Bian, L., Jiang, Z., & Zhang, X. (2019). LEO constellation-augmented multi-GNSS for rapid PPP convergence. *Journal of Geodesy*, *93*(5), 749-764.
43. Jiang, J., Yan, S., & Peng, M. (2018, August). Regional LEO satellite constellation design based on user requirements. In *2018 IEEE/CIC International Conference on Communications in China (ICCC)* (pp. 855-860). IEEE.
44. Qu, Z., Zhang, G., Cao, H., & Xie, J. (2017). LEO satellite constellation for Internet of Things. *IEEE access*, *5*, 18391-18401.
45. Leyva-Mayorga, I., Soret, B., Röper, M., Wübben, D., Matthiesen, B., Dekorsy, A., & Popovski, P. (2020). LEO small-satellite constellations for 5G and beyond-5G communications. *Ieee Access*, *8*, 184955-184964.
46. Su, Y., Liu, Y., Zhou, Y., Yuan, J., Cao, H., & Shi, J. (2019). Broadband LEO satellite communications: Architectures and key technologies. *IEEE Wireless Communications*, *26*(2), 55-61.
47. Leyva-Mayorga, I., Soret, B., Röper, M., Wübben, D., Matthiesen, B., Dekorsy, A., & Popovski, P. (2019). LEO small-satellite constellations for 5G and beyond-5G communications. *arXiv preprint arXiv:1912.08110*.
48. Appel, L., Guelman, M., & Mishne, D. (2014). Optimization of satellite constellation reconfiguration maneuvers. *Acta Astronautica*, *99*, 166-174.
49. Capderou, M. (2002). *Satellites: orbites et missions*. Springer Science & Business Media. Chapter 5 Orbit and Ground Track of a Satellite Available at http://fgg-web.fgg.uni-lj.si/~/mkuhar/Pouk/SG/Seminar/Vrste_tirnic_um_Zemljinih_sat/Orbit_and_Ground_Track_of_a_Satellite-Capderou2005.pdf