

LEO Satellite Performance Comparison under Two Different Elevations

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Abstract

Satellites in LEO (Low Earth Orbits) are closest to the Earth's surface, having the smallest coverage area compared to other orbits, depending on altitude and elevation angle, and providing relatively too short visibility and communication duration, in range of (2 - 15) minutes. Communication duration represents the key performance indicator for LEO satellite communication systems. For longer communication sessions, more satellites must be involved, and the signals must be handed over from one satellite to the next to provide uninterrupted real-time services to the appropriate user or ground station. This leads to the concept and structure of the satellites organized in the constellation. Communication window (visibility window) depends on the designed horizon plane width determined by licensed elevation angle. For the appropriate calculations, a satellite from the *Starlink* constellation at altitude of 550 km is considered, observed under licensed designed elevations of 40° and 25°. Calculations under two designed elevation levels confirmed the wider horizon and consequently longer communication under the lower elevation.

Keywords

Elevation, LEO, Horizon Plane, Satellite, Radar Map

1. Introduction

Compared to terrestrial telecommunication infrastructure, among the advantages of the satellite systems is the coverage of rural and undeveloped areas where the terrestrial infrastructure is too difficult to be implemented because of natural barriers or too high implementation cost.

The State and the Future of LEO Satellite Internet Connectivity in Africa, report of 2022, declares that around 47% of the world's population was still offline in relation to Internet services by the end of 2021 [1]. From this perspective,

international organizations, industry, operators and service providers were seriously engaged to develop the network for ubiquitous broadband Internet services deployment based on satellite network infrastructure. The most convenient infrastructure for such a coverage actually is considered the LEO satellites organized in constellations [2].

The low Earth orbits use the altitudes of 300 km up to around 1400 km above the Earth's surface, and the satellites consolidated to these orbits are known as the LEO satellites, having important advantage over satellites in other orbits since they provide the lowest latency [3].

The actual worldwide social real-time broadband long-distance intercommunications stem from the two emphasized achievements from the last century: 1) the satellite communication systems and 2) the broadband Internet services. Unfortunately, there is still no ubiquitous worldwide coverage with broadband Internet services. Thus, communications-integrated satellite-terrestrial networks are recently seen as the most convenient structure for such global broadband coverage, based on the Low Earth Orbit (LEO) satellites configured and structured as a constellation [3].

The idea and technological efforts towards the integrated satellite-terrestrial network have been enhanced by the appearance of LEO microsattellites at the end of the last century and then also nanosatellites early this century, because it is easier to launch them into space due to their small dimension and light weight [3]. The constellations of micro-nanosatellites currently represent the best model for achieving ubiquitous global Internet broadband coverage.

Iridium constellation with 66 satellites represents the first serious space technological structure, aiming at the time of the implementation to provide worldwide automatic voice communication services [4]. Efforts were then enhanced by OneWeb constellation with 648 satellites [5], and further by Telesat with initiative of 117 satellites organized in constellation [6]. Lastly, the impressive technological and operational activities are taken by SpaceX company, respectively with its constellation defined (named) as *Starlink* [7]. The *Starlink* constellation is foreseen to be organized in three spatial shells, each of them carrying on several hundred LEO microsattellites, specially designed to provide broadband services, through their intercommunication [8] [9].

Thus, in the near future, it should be expected that the worldwide broadband services provided by integrated satellite-terrestrial communication networks will be seriously deployed, increasing the demands for such services, so the operators/providers should apply the appropriate sophisticated end-user devices for the maximized downlink data throughput related to the broadband requirements without significantly affecting the mission cost [10]. Therefore, to provide the largest capacity at the lowest cost, in addition to a need for advanced technology in on-ground receive devices, future satellite payloads and platforms must also become more agile and more adaptable related to customer premises equipment.

LEO passes are characterized by short periods and consequently too short communication windows, which brings the need for optimizing methods to be applied related to the communication between the ground and space segments [11]. In case of a constellation of satellites, the case becomes more complex, so, it is required a sophisticated timely synchronization (orchestration) procedure [12]. These facts confirm too high importance of a visibility-communication window, listing it among key performance indicators in LEO satellites communication process. The visibility-communication window between the LEO satellite and ground station, is directly depended on designed horizon plane width, which is strictly determined by the licensed elevation. Thus, this paper aims to quantify the appropriate difference between two cases, as further elaborated.

Here, we begin with the geometry of satellite and on-ground access point (user or ground station) in space and step by step brought in plane, known as radar map mode of the satellite path. Through the radar map, the concepts of horizon are elaborated towards the designed horizon plane width calculations. For the appropriate analysis, a *Starlink* satellite of the constellation at altitude of 550 km is used, observed under two licensed designed elevation of 40° and 25°.

2. From Space View to the Radar Map Mode

The goal of the satellite systems is to lock the satellite and on-ground Access Point (AP), usually known and used here as the Ground Station (GS), to establish the communication link in between the satellite and the appropriate ground station. Seen from the on-ground access point (ground station), the position of the LEO satellite within its orbit is defined by *azimuth* and *elevation* angles at the ground station's horizon plane. The GS *horizon plane* is assumed as tangent plane (perpendicular) to vector (R_E), which links the ground station location with the Earth's center, as given in **Figure 1**, where the horizon plane is indicated as gray. The angle between vector (R_E) and ground station's horizon plane is denoted with 90° in **Figure 1**, indicating this perpendicularity. The *elevation* (ε_0) is the angle between a satellite and the ground station (user) horizon plane. The elevation ranges from 0° to 90°. The *Azimuth* (Az) is the angle of the direction of the satellite, measured in the horizon plane from geographical north in clockwise direction. The azimuth ranges from 0° to 360° [13]. These two parameters are the most important for the LEO satellite's tracking process seen from the ground station. In **Figure 1**, the triangle with vertices as Earth's center, Ground Station (GS (AP)), and the Satellite (SAT) is bolded. The elevation angle (ε_0) (is measured above the horizon up to the satellite's position), (β_0) is known as central angle and (α_0) is nadir angle. The sides of this triangle are Earth's radius ($R_E = 6871$ km), orbital radius (r) ($r = R_E + H$, where H is orbital altitude), and (d) is the slant range representing the distance between the satellite and ground station seen at time of (ε_0) elevation. The slant range varies depending on elevation (see **Figure 1**) and represents the main parameter to be estimated, since the other two: satellite radius vector (r) and the ground station radius vector (R_E) at any position of

a satellite by the ground station at the horizon plane, and then to keep it under the view as long as possible above the horizon plane. Then, when the satellite is lost from the ground station's view at the horizon plane, the communication between the satellite and the ground station is unlocked. The link is disabled.

Practically, the horizon plane determines the visibility of the satellite from the ground station. The largest possible visibility from the ground station is achieved if the satellite is acquired at elevation of $\varepsilon_0 = 0^\circ$ at the horizon plane and lost also at $\varepsilon_0 = 0^\circ$, known as *ideal horizon plane*.

Two events in space, AOS (acquisition of the satellite) and LOS (loss of the satellite), under elevation of 0° , geographically determine the *ideal horizon plane*, are identified in **Figure 1**. AOS indicates the case when the satellite appears just at the horizon plane to be locked and to initiate communication with the on-ground station (user); LOS (Loss of the Satellite) indicates the case when the satellite just disappears from the horizon plane, being unlocked so that there is no more communication with the ground station. Both of them are characterized with appropriate azimuth, as AOS_{Az} —acquisition of the satellite (azimuth); LOS_{Az} —loss of the satellite (azimuth); and respective events time as AOS_{time} —acquisition of the satellite (time), LOS_{time} —loss of the satellite (time) [16].

Next event that affects satellite paths is the maximal elevation under which one the satellite is seen above the ground station horizon plane. It is denoted Max.El., in **Figure 1**. Max.El. is a characteristic parameter related to each different satellite path. The time taken, from lock, further to Max.El., and then to unlock, determines the visibility and so communication duration between the ground station and the satellite-known as visibility (communication) window. The higher the maximal elevation (Max.El.), the longer is the satellite path above the ground station, so the longer visibility, and definitely the longer communication duration.

The longest possible communication duration, known as *ideal communication duration* between the ground station and the appropriate satellite in its orbital path is theoretically determined as the difference in time between the satellite's appearance on the GS horizon plane (under AOS_{Az} and $\varepsilon_0 = 0^\circ$) and the time when the satellite is lost from the GS horizon plane (LOS_{Az} , $\varepsilon_0 = 0^\circ$), expressed as [13]:

$$Duration_{ideal} = AOS_{time} - LOS_{time} \quad (2)$$

Let us further clarify the satellite's flight over the ground station, based on **Figure 1**. The range between the ground station and the satellite depends on the altitude (H) of the LEO satellite and the elevation angle (ε_0) under which one the satellite is seen above the ground station's horizon plane. Ideally, the satellite appears at elevation of 0° at point AOS_{Az} seen from the ground station and being at the longest distance from the ground station. Since the longest distance refers to the elevation of $\varepsilon_0 = 0^\circ$, it is denoted as (d_0), and applying $\varepsilon_0 = 0^\circ$ at Equation (1) yields out:

$$d_0(\varepsilon_0 = 0) = \sqrt{H(H + 2R_E)} \quad (3)$$

Ideally, the lock should be established at this point. As the satellite flies over the ground station, the elevation increases up to the point of maximal elevation (Max.El.) where the range between the ground station and the satellite is the closest. For the elevation of $\varepsilon_0 = \text{Max.El.}^\circ$, the distance between the ground station and the satellite is denoted as (d_M), and based on Equation (1), it is [16]:

$$d_M (\varepsilon_0 = \text{MaxEl}) = R_E \left[\sqrt{\left(\frac{H + R_E}{R_E} \right)^2 - \cos^2 (\text{MaxEl})} - \sin (\text{MaxEl}) \right] \quad (4)$$

Further from the point of Max.El. (**Figure 1**), the satellite goes symmetrically down, through decreased elevation to point LOS (Loss of Satellite, **Figure 1**) under coordinates of LOS_{Az} and $\varepsilon_0 = 0^\circ$, having again the same distance (d_0). At this point the satellite disappears from the ground station's view, there is no more communication. This leads to conclusion that the ideal horizon plane is in fact the large flat circle laid under zero elevation $\varepsilon_0 = 0^\circ$ for all azimuths ($0 - 360^\circ$), with the center at ground station position, and the radius of $d_0 (\varepsilon_0 = 0)$, as it is given in **Figure 1**. (For practical purposes, only the right side is highlighted, in gray). The above-described process is seen from the ground station; it is automatically followed by the tracking software. For analytical purposes, the space view should be brought on plane. As the satellite moves in its orbit, that movement in space may be projected onto the ground stations' horizon plane [13] [16]. This mode of presentation is known as a "radar map" display.

The radar map mode displays the horizon plane with an accurate position of the ground station at the center. The perimeter of the circle is the horizon plane, with the north on the top ($A_z = 0^\circ$), then at the east ($A_z = 90^\circ$), south ($A_z = 180^\circ$), and west ($A_z = 270^\circ$). Three circles represent elevations 0° , 30° , and 60° . At the center, the elevation is $\varepsilon_0 = 90^\circ$ [13].

Let us try, for the case given as in-space view in **Figure 1**, to bring it into the radar map view. In **Figure 1**, the point LOS_{Az} measured clockwise from the north (N) direction it is roughly around 10° on the left of NS (north-south) direction, and the point AOS_{Az} it is roughly around 145° on the left of NS (north-south) direction. In **Figure 1**, the point of Max.EL., it is roughly at around 45° above the ground station's horizon plane.

Thus, the satellite path seen from the ground station in **Figure 1**, transformed on the radar map mode looks as it is given in **Figure 2**, where the appropriate angles are denoted, also. In **Figure 2**, (d_0) is slant range under 0° and (d_M) is the slant range under Max.EL.

Finally, the flight of the satellite in **Figure 1** will have a different curve on the radar map in **Figure 2** for each different satellite path, it is seen differently from the same ground station because of the movement of the ground station with the Earth's rotation around its N-S (North-South) axis.

Communication under 0° elevation sounds idealistic (ideal horizon plane), and it is almost impossible in an urban environment to ensure communication at zero level of the horizon. The communication under low elevation angles can be

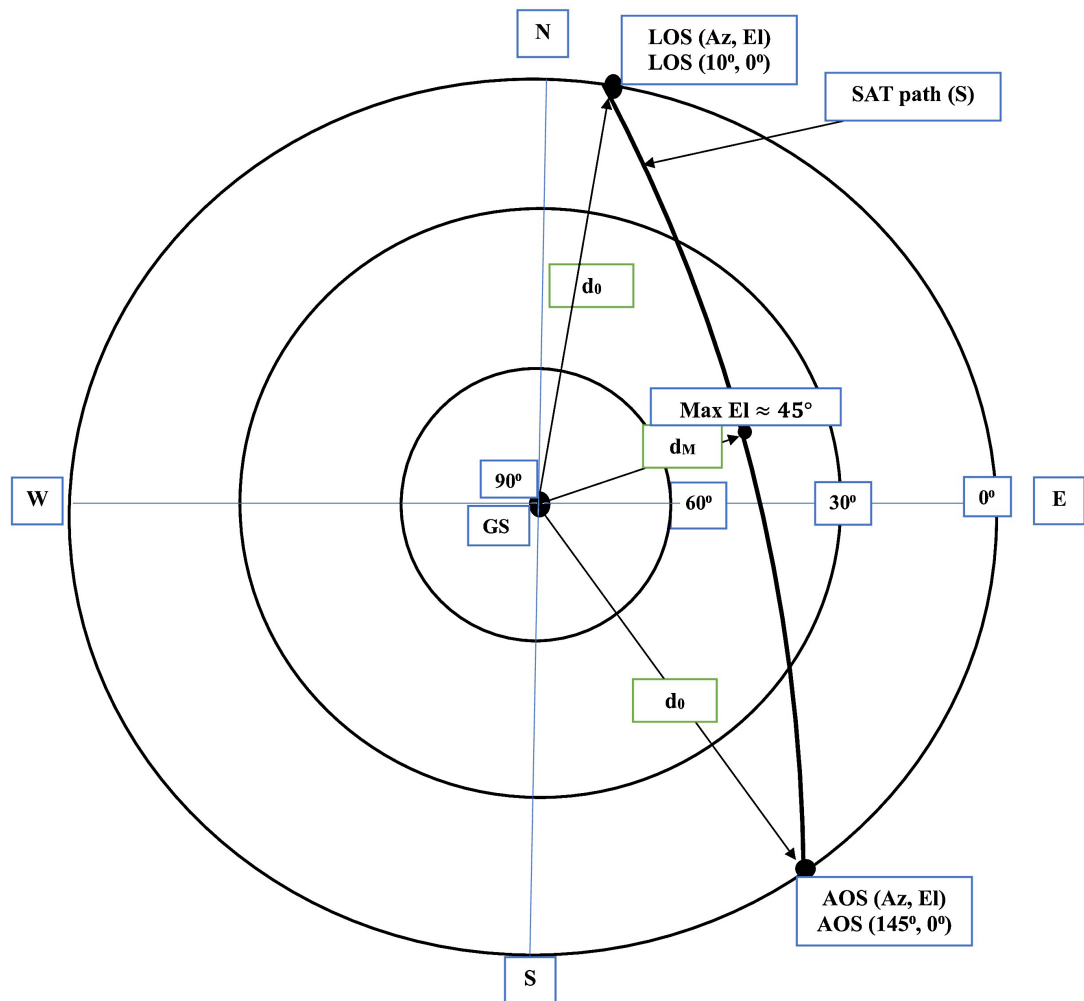


Figure 2. Radar map presentation.

hindered by environmental natural/artificial barriers. Thus, the detection of the satellite above natural/artificial barriers makes the necessity to determine the designed horizon plane, to ensure safe and reliable communication [16]. To avoid the problem of such natural/artificial obstacles, since it is needed to be predetermined in advance the lowest designed elevation of the horizon plane that allows safe lock/unlock, consequently reliable communication. The designed horizon plane is defined by the *minimal elevation* considered for the acquisition and the loss of the satellite. The plane with appropriate *designed elevation* (X°) is considered as the *designed horizon plane*. The designed elevation is licensed by the appropriate regulatory body. For different purposes of the satellite systems, the minimal elevation value for the designed horizon plane ranges on 5° to 55° , thus considering the discussed case, the findings from this paper are aligned and applicable for other practices in satellite communication systems.

3. Horizon Plane Width

For the further discussion a satellite of the *Starlink* constellation is considered.

Starlink constellation is planned to be deployed in three spatial shells, each with several hundred micro satellites, in altitudes of 550 km, 1110 km and 340 km. Nearly 12,000 satellites are planned to be deployed in three shells [17].

The first shell will be occupied by 1440 satellites organized into 72 orbital planes of 20 satellites each, aiming to be completed by the end of 2024 and to serve for real-time Internet broadband services [17]. Initially the first shell (550 km) operated under designed elevation of 40° [18], and later on by FCC (Federal Communications Commission) the designed elevation for users is approved on 25° [19]. Thus, further analysis will provide results under orbit altitude of 550 km for designed elevation of 40° and 25°, aiming to compare the width of the designed horizon under these two licensed elevations. The methodology applied is fully applicable not only for other *Starlink* shells, but also for other constellation based on other altitudes.

3.1. Satellite Motion Parameters

The satellites' behavior is mainly dependent on orbital radius (circular orbits), expressed as:

$$r = R_E + H \quad (5)$$

where H is the orbital altitude and $R_E = 6371$ km is Earth's radius. Further satellite velocity (v), orbital period (T), and number of daily passes (paths) (n) for circular orbit are given as follows:

$$v = \sqrt{\frac{\mu}{r}} \quad (6)$$

$$T = 2\pi\sqrt{\frac{r^3}{\mu}} \quad (7)$$

$$n = \frac{T_S}{T} \quad (8)$$

where (r) is the orbital radius and $\mu = M \cdot G = 3.986 \times 10^5$ km³/s² is constant, as a product of Earth's mass and gravitational Earth's constant, and the number of the daily passes (n) is the ratio of sideral day ($T_{Sideral} = 23$ h 56 min 4.1 s) over the orbital period [3] [13]. For altitude of 550 km, these motion parameters are given in **Table 1**.

Table 1. Satellite motion parameters at altitude of 550 [km].

Motion parameters	Orbit-SAT
Altitude (H) [km]	550
Radius (r) [km]	6921
Velocity (v) [km/s]	7.58
Period (T) [s]	5730.1
Period (T) [min]	95.5
Number of daily passes (n)	15.03

3.2. Radar Map Satellite Path Parameters

The radar map mode of a random orbit and random LEO satellite path (pass), with designed horizon at elevation of 40° and 25° ($\varepsilon_{0,D} = 40^\circ$ and $\varepsilon_{0,D} = 25^\circ$) is given in **Figure 3**. D indicates designed elevation. Bolded circles are two designed horizon elevation levels. Since the elevation of 40° is firstly licensed, firstly will be considered. In **Figure 3**, events as acquisition of the satellite, loss of satellite, are respectively indexed with values 40° and 25° .

Slant ranges are also similarly indexed. Exception is the event of maximal elevation, which is the same for the both cases, since the same path is considered under different designed elevation for comparison purposes.

For the case of designed elevation of 40° , seen from the ground station the satellite is acquired at point A_{40} at azimuth of 225° and elevation of 40° , locked with the ground station, established communication, flying further above the ground station up to maximal elevation of 60° , and then moving down and unlocked at azimuth of 0° and elevation of 40° , when the satellite is lost from the GS view

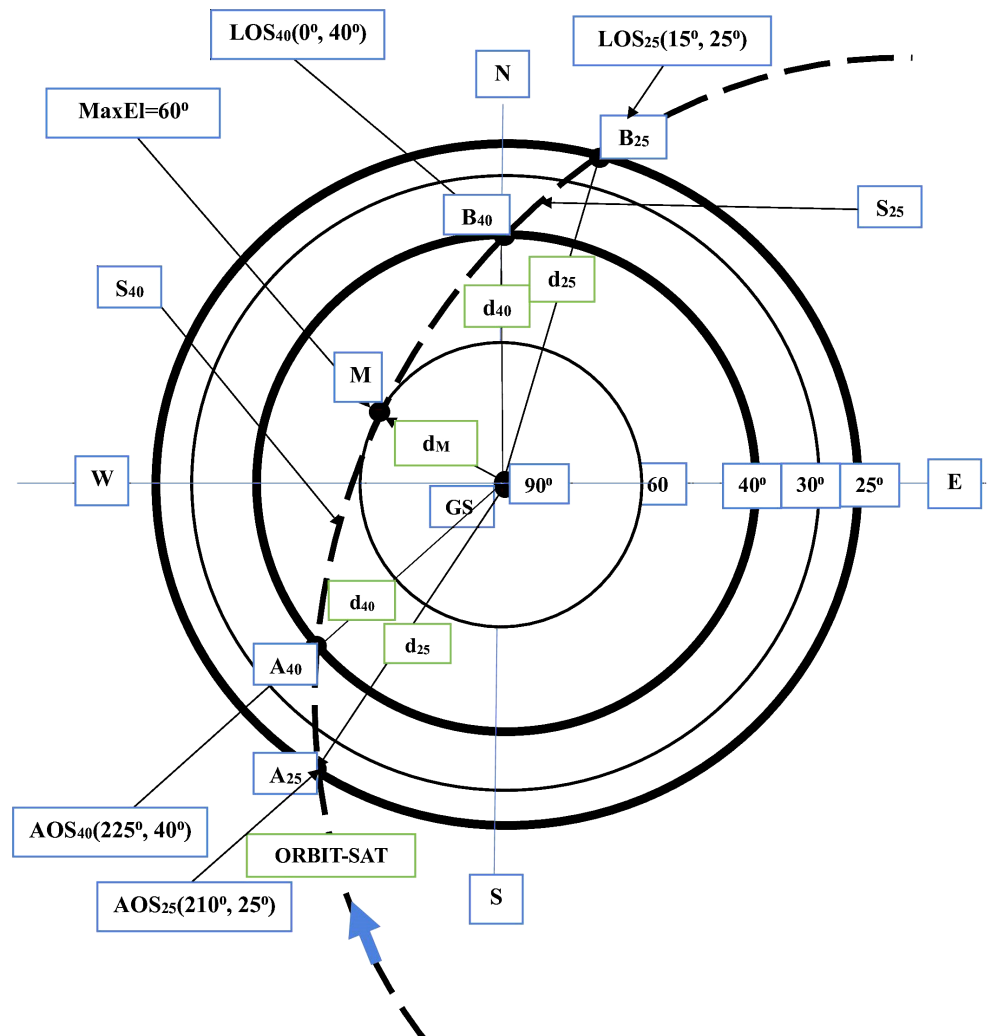


Figure 3. The radar map mode of the random satellite path for designed horizon of 40° and 25° .

at point B_{40} , and there is no more communication between the SAT and GS. Communication between the ground station and the satellites starts at point A_{40} and ends at B_{40} , passing the route S_{40} above the appropriate horizon plane.

For the next case, under 25° , seen from the ground station the satellite is acquired at point A_{25} at azimuth of 210° and elevation of 25° , locked with the ground station, established communication, flying further above the ground station up to maximal elevation of 60° , and then moving down and unlocked at azimuth of 15° and elevation of 25° , when the satellite is lost from the GS view at point B_{25} , and there is no more communication between the SAT and GS. Communication between the ground station and the satellites starts at point A_{25} and ends at B_{25} , passing the route S_{25} above the appropriate horizon plane. Azimuth and loss angles, azimuth separation angle, maximal elevation, slant range under appropriate degree of elevation, determine the satellite path parameters reflected on radar map, further known as radar map path parameters, given in **Table 2** and **Table 3**. For the *Starlink* satellite of altitude at 550km, these parameters are calculated based on Equations (1) and (4) and as tabulated are given in **Table 2** and **Table 3**,

Table 2. Satellite radar map parameters for designed elevation of 40° .

Radar map path parameters	Orbit-SAT
Altitude (H) [km]	550
AOS (Az, El) [$^\circ$]	225; 40
Max.EL. [$^\circ$]	60
LOS (Az, El) [$^\circ$]	0; 40
Azimuth angular separation (ΔAz) [$^\circ$]	135
$d_0(\varepsilon_0 = 0)$ [km]	2703.1
$d_{40}(\varepsilon_0 = 40)$ [km]	813.6
$d_M(\varepsilon_0 = Max.El = 60)$ [km]	626.7

Table 3. Satellite radar map parameters for designed elevation of 25° .

Radar map path parameters	Orbit-SAT
Altitude (H) [km]	550
AOS (Az, El) [$^\circ$]	210; 25
Max.EL. [$^\circ$]	60
LOS (Az, El) [$^\circ$]	15; 25
Azimuth angular separation (ΔAz) [$^\circ$]	165
$d_0(\varepsilon_0 = 0)$ [km]	2703.1
$d_{25}(\varepsilon_0 = 25)$ [km]	1123.3
$d_M(\varepsilon_0 = Max.El. = 60)$ [km]	626.7

respectively for 40° and 25° .

3.3. Designed Horizon Plane Width

The ideal horizon plane represents the visibility region under 0° of elevation angle, as the flat circle with its ideal horizon plane width (*IHPW*). The plane with appropriate designed elevation (X°) is considered as the designed horizon plane, with its designed horizon plane width (*DHPW*) as given in **Figure 4**. Looking from the ground station (user), the designed horizon plane width (*DHPW*) is the base of virtual up napped cone with the apex exactly at the ground station (user). The ground station projected on the designed horizon is denoted as point (C). The designed horizon plane width (*DHPW*) is in fact the diameter of the base of the appropriate virtual cone [3]. Further it is assumed that the designed horizon plane is defined by the lowest elevation $\varepsilon_{0D} = X^\circ$ as is in **Figure 4**. Solving the triangle: ground station (user)—AOS (X°)—center of *DHPW*(C) in **Figure 4** [17], yields out as:

$$DHPW = 2d_{AOS(X)} = 2d(\varepsilon_{0D} = X^\circ) \sin(90 - X) = 2d(\varepsilon_{0D} = X^\circ) \cos X \quad (9)$$

Starlink for the first shell (layer at the altitude of 550 km) applied elevation angle for the designed horizon plane at 40° for users, and latter on is licensed for the elevation of 25° for users.

Applying data from **Table 2** and **Table 3** and Equation (9), yields out as:

$$DHPW_{40} = 2d_{40} \cos 40 \quad (10)$$

$$DHPW_{25} = 2d_{25} \cos 25 \quad (11)$$

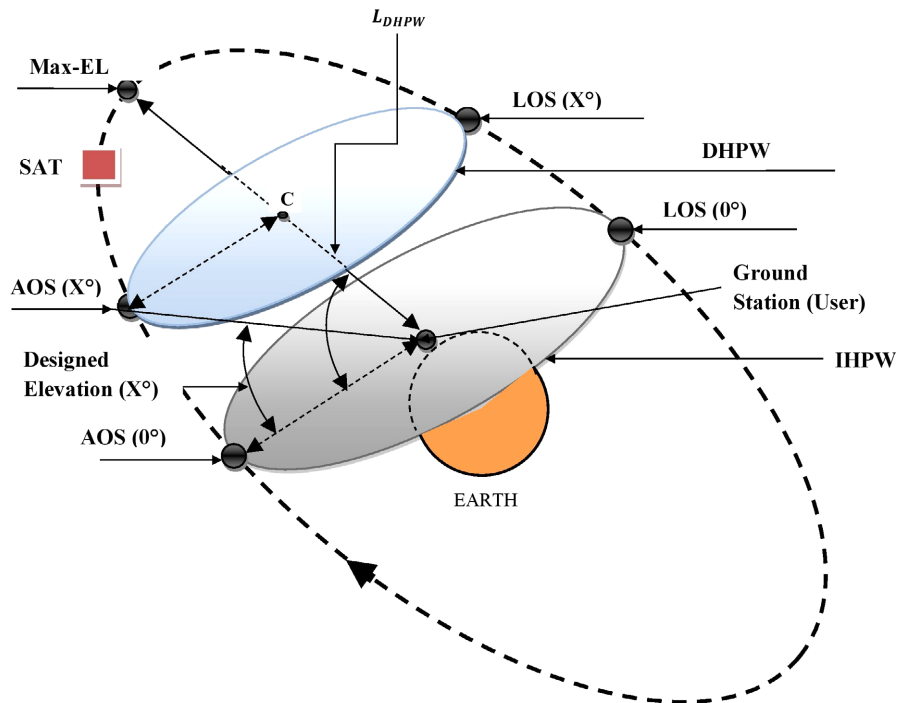


Figure 4. Designed Horizon Plane Width (DHPW).

Applying respective slant range and appropriate elevation it is calculated the designed horizon plane width for both cases, and given as tabulated in **Table 4**.

Table 4. Designed horizon plane width under elevation of 25° and 40° for altitude of 550 [km].

Licensed elevation [°]	Designed horizon plane width (<i>DHPW</i>) [km]
$\varepsilon_{0(40)} = 40$	$DHPW_{40} = 1246.5$
$\varepsilon_{0(25)} = 25$	$DHPW_{25} = 2036.1$

The benefit of applying designed elevation of 25° instead of 40° is obvious, since the first one provides larger designed horizon planes width and consequently longer communication.

4. Conclusions

The communications integrated satellite-terrestrial networks have recently been proven as the most convenient structure for the global broadband coverage, including on-ground access points and Low Earth Orbit (LEO) satellites organized in a constellation.

It is proved that the lower elevation provides wider horizon plane, consequently longer communication duration and longer download/upload Internet sessions provided by the appropriate satellite.

The methodology applied is aligned and applicable to other LEO satellite altitudes.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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