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The Range and Horizon Plane Simulation for Ground Stations of Low Earth Orbiting (LEO) Satellites

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Abstract

Communication via satellite begins when the satellite is positioned in the desired orbital position. Ground stations can communicate with LEO (Low Earth Orbiting) satellites only when the satellite is in their visibility region. The ground station's ideal horizon plane is in fact the visibility region under 0˚ of elevation angle. Because of natural barriers or too high buildings in urban areas, practical (visible) horizon plane differs from the ideal one. The duration of the visibility and so the communication duration varies for each LEO satellite pass at the ground station, since LEO satellites move too fast over the Earth. The range between the ground station and the LEO satellite depends on maximal elevation of satellite's path above the ground station. The dimension of the horizon plane depends on satellite's orbital attitude. The range variations between the ground station and the satellite, and then ground station horizon plane simulation for low Earth orbiting satellites as a function of orbital attitude is presented. The range impact and horizon plane variations on communication duration between the ground station and LEO satellites are given.

Keywords: LEO, Satellite, Range, Horizon

1. Introduction

A typical satellite communication system comprises a ground segment and a space segment. Basic parameters of communication satellites are communication frequencies and orbits. The orbit is the trajectory followed by the satellite. Different types of orbits are possible, each suitable for a specific application or mission. Generally, the orbits of communication satellites are ellipses within the orbital plane defined by orbital parameters [1-3]. Orbits with zero eccentricity are known as *circular orbits*. Circular orbits are presented in **Figure 1** and mainly categorized as:

- GEO (Geosynchronous Earth Orbits)
- MEO (Medium Earth Orbits) and
- LEO (Low Earth Orbits)

Ground stations can communicate with LEO (Low Earth Orbiting) satellites only when the satellite is seen above the ground station's horizon plane. Because of natural barriers practical (visible) horizon is always shorter than ideal one. Natural barriers above the ideal horizon plane create *horizon mask*. In order to avoid such a mask, by implementing also a safe margin, designers determine the *designed horizon plane*. Horizon plane determination enables accurate link budget calculations. Typical cases of designed horizon plane on 5˚ of elevation are ground stations of LEO satellites dedicated for search and rescue services [4]. Another example of higher designed horizon plane is for ground station dedicate for communication with LEO satellite for ionosphere monitoring [5].

Logical order of designed horizon plane determination is proceed with an in advance ideal horizon plane and respective horizon mask determination. Within this paper we are limited only on ideal horizon plane simulation.

A general concept of a horizon plane is presented at second section. The satellite and ground station geometry for LEO satellites is briefly described. The range and ground station horizon plane simulation for LEO satellites is finally given for different satellite attitudes under different maximal elevation angles.

2. Horizon Plane

The *horizon plane* is considered a tangent plane to the surface of the Earth at the observer's position (ground

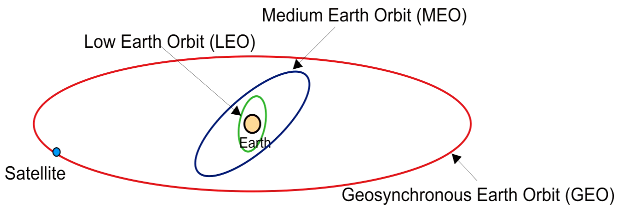

Figure 1. Satellite orbits.

station). The position of the satellite within its orbit considered from the ground station point of view can be defined by *Azimuth* and *Elevation* angles. The concept of azimuth, elevation and horizon plane is presented in **Figure 2**.

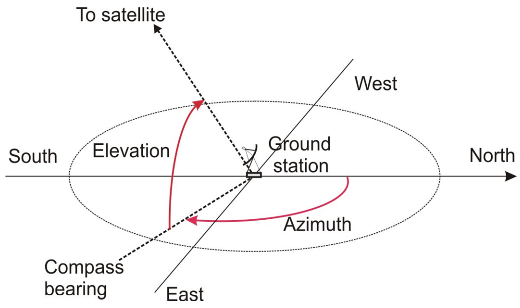

Figure 2. Azimuth, elevation and horizon plane.

The azimuth (*Az*) is the angle of the direction of the satellite, measured in the horizon plane from geographical north in clockwise direction. The range of azimuth is 0˚ to 360˚. The elevation (*El*) is the angle between a satellite and the observer's (ground station's) horizon plane. The range of elevation is 0˚ to 90˚. The ellipse in **Figure 2** represents the ideal horizon plane seen from the observer's (ground station).

For tracking the satellite, Kepler elements (space orbital parameters [1-3]) are fed to orbit determination software which calculates the actual position of the satellite. A software process running at the ground station uses these parameters to precisely determine the time when the satellite will communicate with the ground station and prepares the ground station's antenna in advance to wait for the upcoming pass of the satellite [4,6]. For LEO satellites the communication is locked when the satellite shows up at the horizon plane. The respective software provides real-time tracking information, usually displayed in different modes (satellite view, radar map, tabulated, etc.). The "radar map" mode includes accurate satellite path with the ground station considered at the center, as in **Figure 3** presented [3,6].

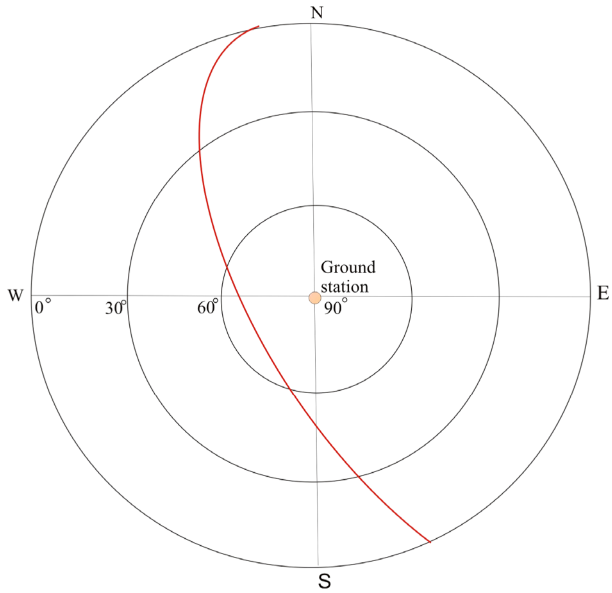

Figure 3. Radar map display.

The perimeter of the circle is *the horizon plane*, with North on the top (*Az* = 0˚), then East (*Az* = 90˚), South (*Az* = 180˚) and West (*Az* = 270˚). Three concentric circles represent different elevations: 0˚, 30˚ and 60˚. At the center the elevation is *El* = 90˚. Most usual software parameters which define the movement of the satellite related to the ground station are: AOS_{time}—Acquisition of the satellite (time), LOS_{time}—Loss of the satellite (time), AOS_A—Acquisition of the satellite (azimuth), AOS_{El}—Acquisition of the satellite (elevation), LOS_{Az}—Loss of the satellite (azimuth), LOS_{El}—Loss of the satellite (elevation), *MaxEl*—Maximal Elevation. Looking at **Figure 3** the line crossing circles is projection of the satellite's path on horizon plane. Considering the case of ideal horizon plane ($AOS_{El} = LOS_{El} = 0^\circ$), at **Figure 3** the other approximate values of satellite's parameters are $AOS_{Az} \approx 350^\circ$, $LOS_{Az} \approx 165^\circ$ and $MaxEl \approx 50^\circ$.

For LEO satellites, the maximal elevation is very important parameter which in fact determines the communication duration between LEO satellite and respective ground station.

The plane at 0˚ elevation represent ideal horizon plane. If it is considered the whole horizon in the azimuth range of 0˚ - 360˚, in any direction of the horizon plane the natural barriers will differ; consequently so will the acquisition and loss elevation. The practical elevation values ranges from 1˚ - 4˚ [6]. Practical (visible) horizon is always shorter than ideal one, reflecting on shorter communication time between the satellite and the ground station. So, the communication time depends on the maximal elevation, and on the practical horizon [7]. In order to avoid the problem of natural barriers, designers predetermine the lowest elevation of the horizon plane which is applied during link budget calculations. Considering a safe margin, this elevation ranges from 5˚ - 30˚ [4-6]. The horizon plane with a predetermined minimal elevation is considered the *designed horizon plane* [7].

3. Slant Range for LEO Satellites

The basic geometry between a LEO satellite and ground station is depicted in **Figure 4**.

The two points indicate the satellite (SAT) and ground station (P), and then the third is the Earth's center. The subsatellite point is indicated by T (T is the point where the joining line of the satellite and Earth's center intersect the Earth's surface). Distance d represents slant range between a satellite and ground station. This range changes over time since the satellite flies too fast above the ground station. In **Figure 4**, the radius r is:

$$r = R_E + H \quad (1)$$

R_E = 6378 km is Earth's radius and H is LEO satellite's attitude. The line crossing point P indicates tangent plane to Earth's surface at point P, what by definition is in fact ideal horizon plane. The angle formed between ideal horizon plane and the slant range is elevation angle ε_0. The triangle from **Figure 4** brought in plane looks like in **Figure 5** [8].

Two sides of this triangle are usually known (the distance from the ground station to the Earth's center R_E = 6378 km, and distance form the satellite to Earth's center-orbital radius). The angle under which the satellite sees the ground station is called *nadir angle*. There are four variables in this triangle: ε_0—is elevation angle, α_0—is nadir angle, β_0—is central angle and d is slant range. As soon as two quantities are known, the others can be found with the following equations [8]:

$$\varepsilon_0 + \alpha_0 + \beta_0 = 90 \quad (2)$$

$$d \cos\varepsilon_0 = r \sin\beta_0 \quad (3)$$

$$d \sin\alpha_0 = R_e \sin\beta_0 \quad (4)$$

The most asked parameter is the slant range d (distance from the ground station to the satellite). This parameter will be used during the link budget calculation, and it is expressed through elevation angle ε_0. Applying cosines law for triangle at **Figure 5** yields:

$$r^2 = R_E^2 + d^2 - 2R_E d\cos(90+\varepsilon_0) \quad (5)$$

Solving Equation (5) by d, yields:

$$d = R_E\left[\sqrt{\left(\frac{r}{R_E}\right)^2 - \cos^2\varepsilon_0} - \sin\varepsilon_0\right] \quad (6)$$

Substituting, $r = H + R_E$ at Equation (6) finally we will get the slant range as function of elevation angle ε_0:

$$d = R_E\left[\sqrt{\left(\frac{H+R_E}{R_E}\right)^2 - \cos^2\varepsilon_0} - \sin\varepsilon_0\right] \quad (7)$$

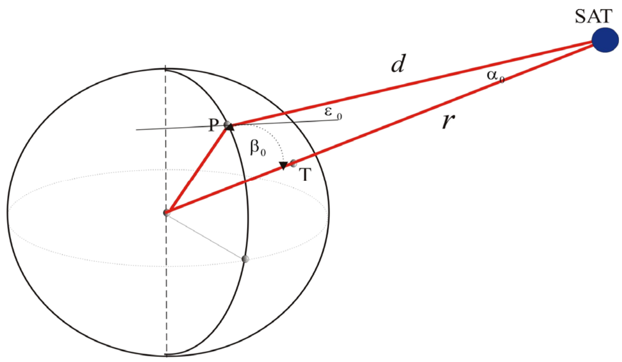

Figure 4. Ground station geometry.

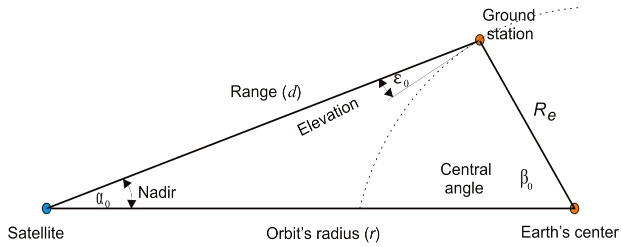

Figure 5. Ground station geometry.

or elevation ε_0 expressed for known slant range d as:

$$\sin\varepsilon_0 = \frac{H(H+2R_E)-d^2}{2dR_E} \quad (8)$$

For $d^2 = H(H+2R_E)$ yields out $\sin\varepsilon_0 = 0 \Rightarrow \varepsilon_0 = 0$, for $d = H$ yields out $\sin\varepsilon_0 = 1 \Rightarrow \varepsilon_0 = 90^\circ$.

The range under the lowest elevation angle represents the worst link budget case, since that range represents the maximal possible distance between the ground station and the satellite. More power is required to overcome larger distance. Thus a trade off should be applied, in order to optimize the required transmit power and the designed horizon plane.

4. Horizon Plane Simulation for Ground Stations of LEO Satellites

LEO satellites have very wide applications, from remote sensing of oceans, through analyses on Earth's climate changes, Earth's imagery with high resolution or astronomical purposes [9]. LEOs are just above Earth's atmosphere, where there is almost no air to cause drag on the satellite and reduce its speed. Less energy is required to launch a satellite into this type of orbit than into any other orbit [2,3]. LEO altitudes range from 275 km up to 1400 km limited by Van Allen radiation effects (sensors, integrated circuits and solar cells can be damaged by this radiation) [10].

Goal of this simulation is to conclude about slant range and horizon plane variations for a ground station dedicated to communicate with LEO satellite. As input simulation parameters (based on Equation (7)) are considered maximal elevation angle of the satellite's path above the respective ground station and LEO satellite's attitude. Considering Van Allen belt effect, for simulation purposes are considered attitudes form 600 km up to 1200 km. Simulation expected output is slant range variations.

For these attitudes applying Equation (7) it is calculated the range from a hypothetical ground station, presented at **Table 1**, and graphically in **Figure 6**. From **Figure 6** it is obvious that the shortest range occurs at 90˚ elevation, since the satellites appears perpendicularly above the ground station [6]. At 90˚ elevation, the slant range is the shortest and it equals with satellites attitude *H*.

From **Figure 6**, the largest range is achieved under 0˚ elevation, representing the radius of the circle of an ideal horizon plane seen from the ground station. Mathematically expressed, as:

$$d_{max} = d_{(\varepsilon_0 = 0)} \tag{9}$$

This range increases as satellite's attitude *H* increases. The ideal horizon planes for different satellite attitudes, considering d_{max} ranges from **Table 1** or **Figure 6** in **Figure 7** is presented.

Figure 7 confirms the expansion of horizon plane as satellite attitude increases. For respectively, the lowest and the highest considered satellite's attitude of *H* = 600 km and *H* = 1200 km the ranges are:

$$d_{max(H=600)} = 2830 \text{ km}$$

Table 1. LEO satellite ranges.

Orbital Attitude [km]	*H* 600	*H* 700	*H* 800	*H* 900	*H* 1000	*H* 1100	*H* 1200
Max *El* (ε_0)	Range [km]	Range [km]	Range [km]	Range [km]	Range [km]	Range [km]	Range [km]
0˚	2830	3065	3289	3504	3708	3900	4088
10˚	1942	2180	2372	2577	2770	2955	3136
20˚	1386	1581	1765	1947	2120	2287	2453
30˚	1070	1234	1392	1549	1701	1849	1996
40˚	886	1027	1164	1302	1436	1567	1698
50˚	758	883	1005	1128	1248	1366	1486
60˚	680	794	905	1018	1129	1238	1348
70˚	636	742	847	954	1058	1160	1266
80˚	697	707	809	908	1012	1113	1214
90˚	600	700	800	900	1000	1100	1200

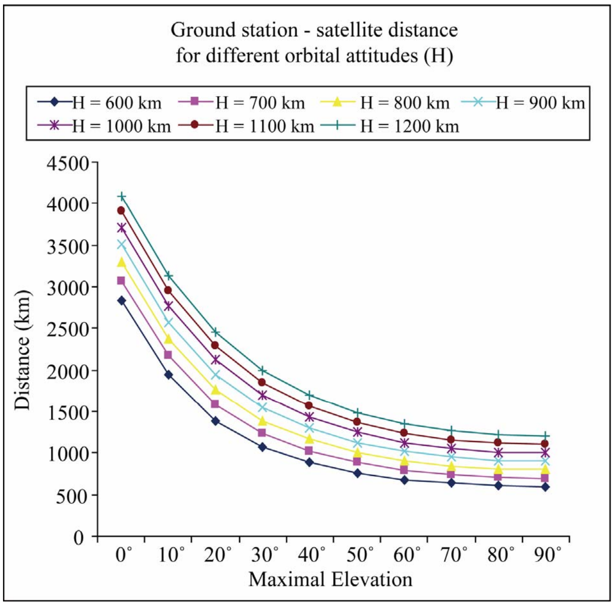

Figure 6. Stellite range for LEO orbits.

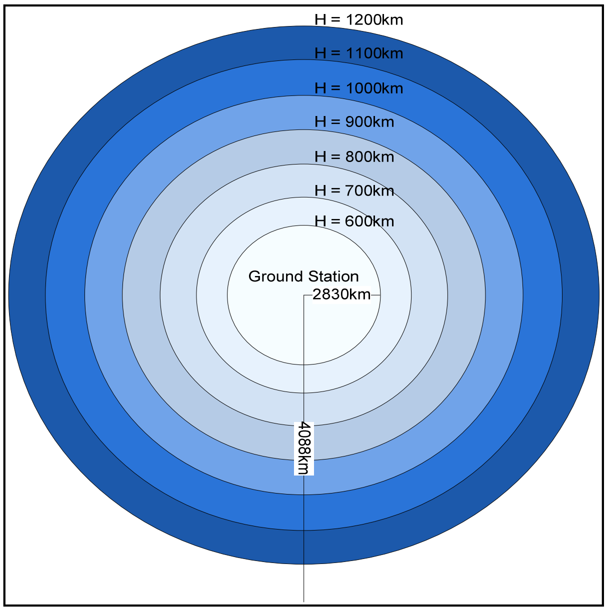

Figure 7. Ideal horizon planes.

$$d_{max(H=1200)} = 4088 \text{ km}$$

The ideal horizon planes of ground stations dedicated to communicate with LEO satellites of attitudes from (600 - 1200) km may be considered as ideal flat circles with diameter from 5660 km to 8176 km.

Within these horizon planes the communication can be locked between the LEO satellites and appropriate ground stations. Communication duration will depend on maximal elevation of satellite's path above the respective horizon plane.

Considering above analysis, the communication duration between LEO satellites and the appropriate ground station usually takes (5 - 15) minutes, few times (6 - 8) during the day. This too short communication time makes necessity for horizon plane determination as a precondition of optimized communication (data download) between the LEO satellite and respective ground station.

5. Conclusions

The communication duration between the LEO satellite and respective ground station depends on maximal elevation of satellite's path over the ground station and largeness of the horizon plane.

For ground stations dedicated to communicate with LEO satellites the ideal horizon plane can be considered as a flat circle with diameter ranging approximately from 6000 km to 8000 km. Because of natural barriers or too high buildings in urban areas, practical horizon plane always differs (smaller) from the ideal one.

Through simulation it is confirmed that the horizon plan expands as satellite's attitude increases, consequently providing longer communication between satellite and appropriate ground station.

Considering the ideal horizon plane and the respective mask because of natural barriers, ground station designers by applying a safe margin, successfully define the designed horizon plane for the planned satellite ground station to be installed.

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