Practical Horizon Plane for Low Earth Orbiting (LEO) Satellite Ground Stations

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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 duration of the visibility and so the communication duration varies for each satellite pass at the ground station, specifically for LEO satellites which do move too fast over the Earth [1]. For low cost LEO satellite ground stations in urban environment it will be a big challenge to ensure communication down to the horizon. The communication at low elevation angles can be hindered through natural barriers. Thus, motion (appearance) detection of the satellite above natural barriers enables the practical horizon to be determined. Practical horizon differs from the ideal horizon. This paper discusses the satellites motion detection and the difference in between ideal and practical horizon. For this paper, data recorded at the Vienna satellite ground station within the Canadian space observation project "MOST" (Micro variability and Oscillations of Stars) are applied. Vienna ground station system was set up at the Institute for Astronomy of the University of Vienna in cooperation with the Institute of Communications and Radio- Frequency Engineering of the University of Technology.

Key-Words: - LEO, satellite, horizon, elevation

1 Introduction

The typical satellite communication system comprises of a *ground segment*, *space segment* and *control segment*. The link which transmits radio waves from the ground station to the satellite is called *uplink*. The satellite in turn transmits to the ground station by the *downlink*. The function of the *ground segment* (one or more ground stations) is to receive or transmit the information to the satellite in the most reliable manner while retaining the desired signal quality. The *space segment* consists of one or more artificial satellites. In case of more satellites they are organized in a network called *constellation*. The *control segment* consists of all ground facilities for control and monitoring satellite. The *coverage area* (footprint) is defined as a region on the Earth from where the satellite is seen under the lowest elevation angle. The communication between the satellite and a ground station is established only when the satellite is visible from the ground station [2].

2 Orbits

The basic resources available for communication with satellites are *radio frequency spectrum* (RF) and *orbits*. Frequency allocations are treated by international agreements. The orbit is the trajectory followed by the satellite. Several 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 space orbital parameters. Orbits with zero eccentricity are called *circular orbits*. The circularity of the orbit simplifies the analysis. The movement of the satellite within its circular orbit is represented by *orbital time, radius, altitude* and *velocity*. Circular orbits are categorized based on the altitude above Earth's surface as presented in Fig. 1.

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

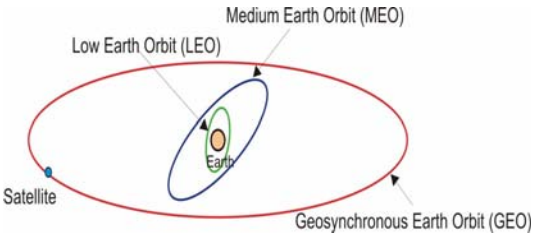


Fig. 1. Satellite orbits

2.1 Low Earth Orbits

Low Earth Orbits (LEOs) are just above Earth's atmosphere, where there is almost no air to cause drag on the satellite and reduce its speed. Satellites that point toward deep space dedicated to provide scientific space information generally operate in this type of orbit. The Hubble Space Telescope, for example, operates at an altitude of about 610 km with an orbital period of 97 minutes [3]. LEO altitudes range from 275km up to 1400km limited by Van Allen radiation effects (sensors, integrated circuits and solar cells can be damaged by this radiation) [4]. Satellites in these orbits have an orbital period of around (90-110) minutes. For satellites this is a short flyover period, which means that the antenna at the ground station must follow the satellite very fast with high pointing accuracy. The contact communication time between the satellite and the ground station takes (5-15) minutes 6-8 times during the day [5]. Mismatch in pointing will lead to a decrease of received signal strength and further to a reduction of the communication quality.

2.2 Constellation

The constellation is a system of low (medium) Earth orbit (LEO or MEO) identical satellites, launched in several orbital planes with the orbits having the same altitude. The satellites move in a synchronized manner in trajectories relative to Earth. The application of low Earth orbit satellites organized in a *constellation* is an alternative to wireless telephone networks. Satellites in low orbits arranged in a constellation, work together by relaying information to each other and to the users on the ground. If satellites within a constellation are equipped with advanced on-board processing, they can communicate directly with each other by line of sight using inter-satellite links (ISL). If the ISL is between satellites in the same orbit, it is called intra-plane ISL, and if it is between satellites in adjacent planes it is called inter-plane ISL. The GPS (Global Positioning System) constellation is presented in Fig. 2[6].

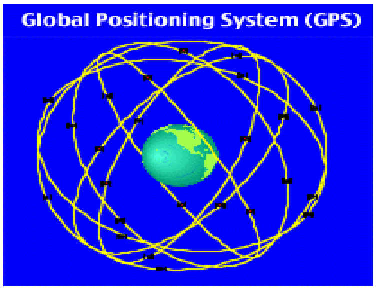


Fig. 2. GPS constellation

This constellation is organized in 6 orbital planes of 4 satellites per plane (24 satellites). Each satellite circles the Earth twice a day.

3 Space Orbital Parameters

The path of the satellite's motion is an orbit. The orbit is a trajectory within an orbital plane and shaped as an ellipse, with a maximum extension from the Earth center at the *apogee* (r_a) and the minimum at the *perigee* (r_p) as presented in Fig. 3[7].

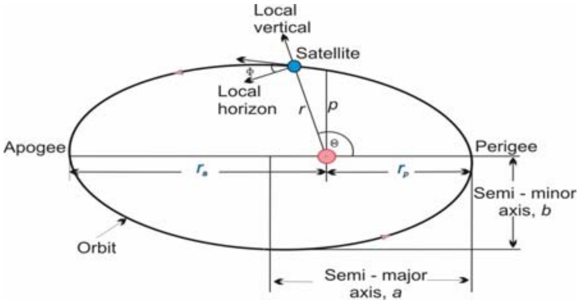


Fig. 3. Major parameters of an elliptical orbit

In order to describe the satellite's movement within its orbit in space, a few parameters are required to be defined. These are known as *space orbital parameters* schematically presented in Fig. 4 and defined under below items a), b), c) and d) [8].

a) *The position of the orbital plane in space.*

This is specified by means of two parameters - the *inclination i* and the *right ascension of the ascending node Ω*. Inclination *i* represents the angle of the orbital plane with respect to the Earth's equator. The right ascension of the ascending node *Ω* defines the location of the ascending and descending orbital crossing nodes (these two nodes make a *line of nodes*) with respect to a fixed direction in space. The fixed direction is Vernal equinox. Vernal equinox is direction of line joining the Earth's center and the Sun on the first day of spring [9].

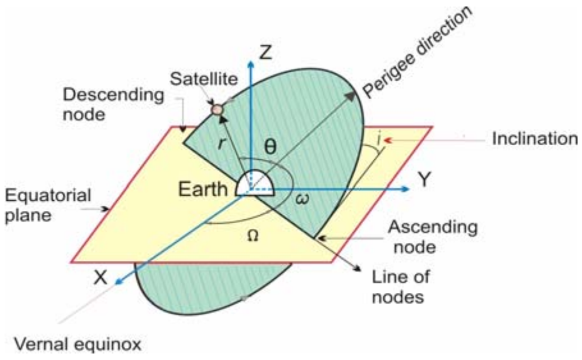


Fig. 4. Space orbital parameters

b) *Location of the orbit in orbital plane.*
Normally an infinite number of orbits can be laid within an orbital plane. So, the orientation of the orbit in its plane is defined by the *argument of perigee ω*. This is the angle, taken positively from 0º to 360º in the direction of the satellite's motion, between the direction of the ascending node and the direction of perigee [7]-[9].

c) *Position of the satellite in the orbit.*
The position of the satellite in orbit is determined by the angle θ called the *true anomaly,* which is the angle measured positively in the direction of satellite's movement from 0º to 360º, between the direction of perigee and the position of the satellite [7]-[9].

d) *The shape of orbit*.
The shape of orbit is presented by the *semi-major axis a* (Fig. 3) which defines the size of orbit and the *eccentricity* e which defines the shape of the orbit. The eccentricity is the ratio of difference to sum of apogee (r_a) and perigee (r_p) radii.

4 Tracking of the satellite

The Earth rotates from East to West. This is known as eastward direction, the opposite is called westward direction. An orbit in which satellite moves in the same direction as the Earth's rotation is known as *prograde* or *direct orbit.* An orbit in which the satellite moves in opposite direction to Earth rotation is called *retrograde orbit*, as in Fig. 5 is presented. The inclination of a prograde orbit always lies between 0º and 90º (Fig. 4). The inclination of a retrograde orbit always lies between 90º and 180º.

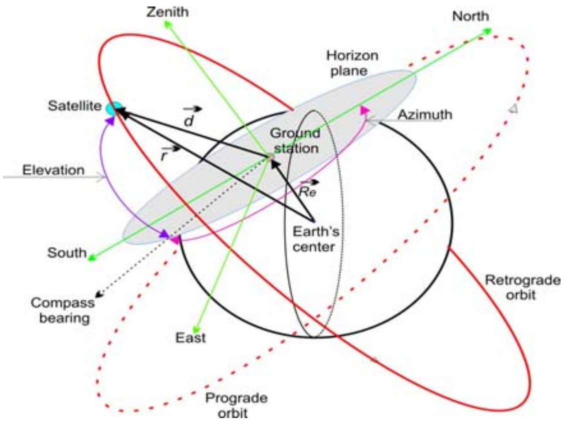


Fig. 5. Orbit and ground station

In Fig. 5, vectors $\vec{r}$, $\vec{d}$ and $\vec{R}_e$ represent respectively, vector from the Earth's center to satellite, vector from the ground station to satellite and vector from the Earth's center to ground station. It is obvious the relationship as:

$$\vec{d} = \vec{r} - \vec{R}_e \tag{1}$$

The position of the satellite within its orbit considered from the ground station point of view is defined by *Azimuth* (*Az*) and *Elevation* (*El*) angles. The azimuth 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 0º to 360º. The elevation is the angle between a satellite and the observer's (ground station's) horizon plane, as presented in Fig. 5. The range of elevation is 0º to 90º. For tracking the satellite a tracking mechanism and appropriate software is used. As inputs Keplerian elements are used calculating the actual position of the satellite. The respective software provides real-time tracking information, usually displayed in "radar map". The display mode of "radar map" includes the accurate satellite's position with the ground station considered at the center, as in Fig.6 presented.
The perimeter of the circle is the horizon plane, with the North on the top (*Az* = 0º), then at the East (*Az* = 90º), South (*Az* = 180º) and West (*Az* = 270º). Three circles represent different elevation 0º, 30º and 60º. At the center the elevation is *El*=90º. 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_{Az}– Acquisition of the satellite (azimuth), LOS_{Az} – Loss of the satellite (azimuth), *Max El*- Maximal Elevation and *Orbit* – Orbit number.

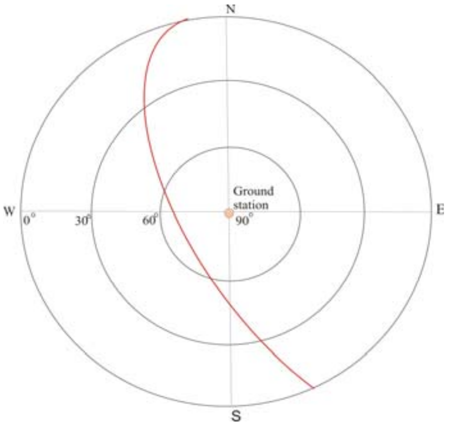
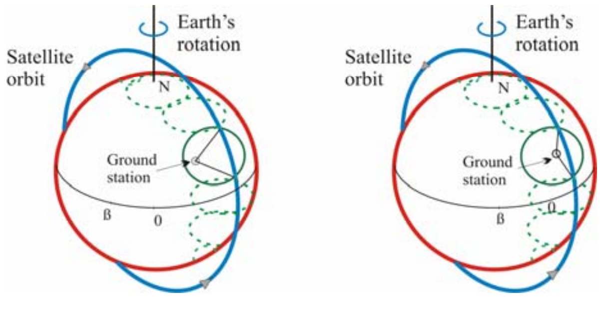


Fig. 6. Radar map presentation

The satellite's movement (satellite's pass) is presented with satellite's path in radar map (red line), what in fact is the satellite's orbit projection on the horizon plane (Fig. 6). The communication duration is defined as:

$$Duration = AOS_{time} - LOS_{time} \qquad (2)$$

and represents the maximum theoretical time duration of the communication between the satellite and ground station. The orbital plane is in principle fixed and defined by orbital parameters (see Fig. 4). Because of Earth's rotation around its N-S axis for angle β, as depicted in Fig. 7, the ground station changes the position relatively to orbital plane, so the pointing (azimuth and elevation) from the ground station to the satellite is not identical for the both satellite passes (see a) and b) in Fig. 7) [2],[8]. This is typical for LEO satellites which move too fast over the Earth.



a) b)

Fig. 7. Satellite pass for an Earth rotation angle of β per orbit a) first pass and b) second pass.

Hence the communication duration between the satellite and the ground station is not constant and varies for each orbit path. Each orbit path is characterized with *Max El.* The duration time of communication expressed in Eqn. 2 is based on Kepler's laws and represents the theoretical time duration, considering the acquisition and loss of satellite under 0º elevation [2]. But, practically the acquisition and loss of satellite do not occur at 0º elevation, because of natural barriers or misspointing. So, the communication time depends on one hand on the maximum elevation [2] and on the other hand on the practical radio horizon. Within this paper the problem of practical horizon is considered, applying data recorded at the Vienna satellite ground station within the Canadian space observation project "MOST" (Micro variability and Oscillations of Stars) [5], [10].

5 MOST Satellite and Vienna Ground Station

Most satellites are launched in a prograde orbit because the Earth's rotational velocity provides part of the orbital velocity with a consequent saving in launch energy [7]-[9]. The project "MOST" is a Canadian micro satellite space telescope mission. The size of the satellite is 65cm x 65cm x 30cm and the mass is about 65kg. The goals of the mission are: to analyze the inner structure of stars, set a lower limit to the age of the universe and to search for Exoplanets, by picking up tiny light variations of stars [10]. The project "MOST" consists of a Low Earth Orbiting (LEO) Satellite and three Ground Stations, one of them in Vienna [5]. The idea of "MOST" satellite is depicted in Fig. 8 [10].

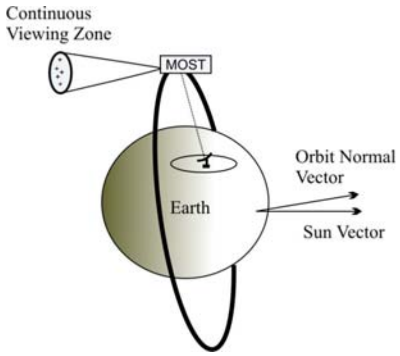


Fig. 8. MOST satellite idea

The baseline orbit of MOST is a sun-synchronous orbit, with 98º inclination and an altitude of around 820 km [10].

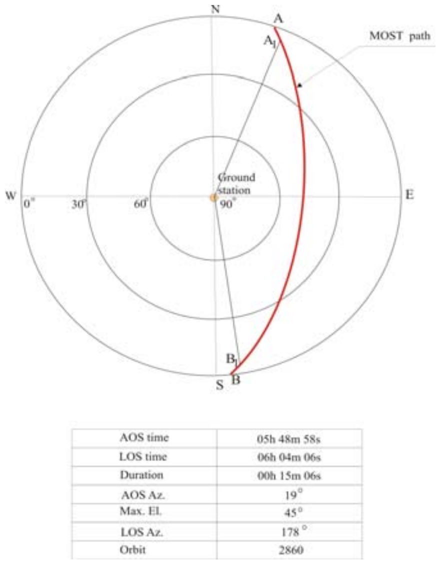
The Vienna ground station system was set up at the Institute for Astronomy of the University of Vienna in cooperation with the Institute of Communications and Radio-Frequency Engineering of the Vienna University of Technology. The ground station must track the satellite during its flyover keeping a pointing accuracy of 0.5º [5]. The ground station can interact with the satellite only if it is visible above the horizon and therefore for a fraction of few orbits per day. The tracking software used for "MOST" is called *Nova* [11]. The visibility region of the Vienna satellite ground station is shown in Fig. 9.

Fig. 9. Visibility region of Vienna ground station for elevation angle of 0° [11].

The MOST satellite has a line of sight radio contact with the Vienna ground station 6-8 times per day. The communication duration time of each satellite pass will last between 5-15 minutes [5], [10].

5.1. Practical Horizon

In Fig.10, one of the MOST satellite paths with respective data is presented [2].



AOS time	05h 48m 58s
LOS time	06h 04m 06s
Duration	00h 15m 06s
AOS Az.	19°
Max. El.	45°
LOS Az.	178°
Orbit	2860

Fig. 10. MOST path

Theoretically, based on Kepler's laws, the communication between the satellite and the ground station should be established at point *A* (*Az* = 19º under 0º elevation) and communication should be lost at point *B* (*Az* = 178º under 0º elevation) at Fig. 10. No contact to the satellite could be established under the 0º elevation, because of natural barriers or misspointing. Practically contact between the satellite and ground station is established at point A_1 and lost at point B_1 (both under elevation of few degrees). Thus, points A and B belong to ideal horizon plan, otherwise A_1 and B_1 belong to practical horizon. In order to create better picture of practical horizon at Vienna satellite ground station appropriate data about acquisition (*AEl*) and lost elevation (*LEl*) for different orbits are recorded. Few of these records are presented in Table 1.

Table 1. Orbit records at Vienna ground station

Orbit	*AAz*	*AEl*	*MaxEl*	*LAz*	*LEl*
xxxx	o	o	o	o	o
2639	170	1.0	72	340	2.5
2652	107	1.0	16	7	5.0
2662	350	4.0	10	270	5.0
2676	352	4.0	14	258	3.0
2709	122	1.0	22	2	5.0
2737	95	1.0	12	8	5.0
2759	49	6.0	13	139	1.0
2760	15	4.0	84	190	4.0
2817	36	6.0	21	154	1.0
2879	103	1.5	14	14	7.0
2907	61	6.0	7	20	4.5
2945	26	5.0	34	163	7.0
2947	347	3.0	7	276	1.5
2965	149	2.0	56	350	2.0
2966	206	4.0	24	331	3.0
2987	43	4.0	11	129	3.0
3009	236	3.5	10	315	4.0
3066	253	2.0	5	302	4.0
3072	79	7	8	118	3.0
3136	187	3.5	41	337	3.5
3160	339	3.0	6	290	2.5
3193	203	5.5	27	332	3.0
3251	215	3.0	17	327	3.0
3302	324	4.5	5	300	3.0
2992	65	2.0	5	23	4.0

Data recorded at Vienna ground station (included those from Table 1) are pointed in radar map view, presented in Fig. 11.

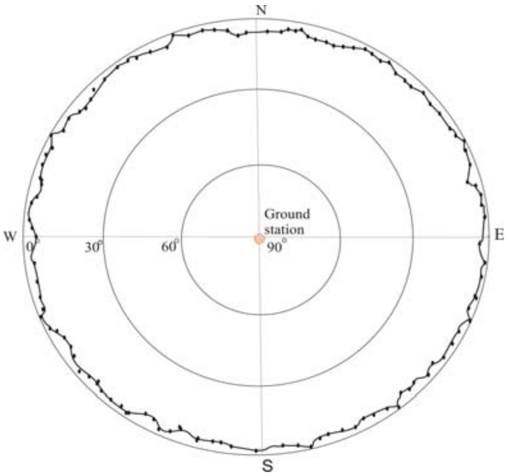


Fig. 11. Practical horizon plane

The inner line (darker one) related to the largest circle is in fact the practical horizon. It is obvious that the practical horizon is always shorter than ideal one, reflecting on shorter communication time between the satellite and the ground station.

6 Conclusion

Motion detection enables practical horizon determination. Obviously practical horizon differs from the ideal one, for around 2º-3º degrees of elevation in average, because of natural barriers. This is confirmed based on records at Vienna satellite ground station. Considering that for LEO satellites the contact between satellite and ground station is in range of (3-15) minutes, this difference impacts communication duration, also. This effect should be considered specifically on constellations design because of hand over process under low elevations.

Acknowledgement

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