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Hossein Bonyan Khamseh
Shahid Beheshti University, GC
Tehran − Iran
h.bonyan@gmail.com

M. Navabi*
Shahid Beheshti University, GC
Tehran − Iran
navabi.edu @gmail.com

*author for correspondence

On reduction of longest accessibility gap in LEO sun-synchronous satellite missions

Abstract: *Accessibility gaps are inherent properties of Low Earth Orbit (LEO) sun-synchronous satellite missions. Long accessibility gaps in satellite missions imply strict in-orbit autonomy requirement, met by expensive solutions. Thus, methods to shorten accessibility gaps in satellite missions are appreciated by space mission designers. For that purpose, in this paper, ground segment site location is employed as a mechanism to reduce the longest accessibility gaps in LEO sun-synchronous missions. For a given repeatability cycle, it is shown that longitude of the ground segment does not affect the access gaps. Simulation results show that increasing the latitude of ground segment reduces the longest accessibility gaps, especially in extreme latitudes near Polar Regions. To avoid polar ground segments due to their practical difficulties, mission architectures with two co-high-latitude ground segments are proposed. Selection of longitude distance between the two co-high-latitude ground segments is discussed to further reduce the longest accessibility gap in LEO sun-synchronous missions. To show the feasibility of the proposed approach, simulation results are included for illustration.*
Keywords: *Ground segment location, LEO sun-synchronous satellite, Longest accessibility gap.*

INTRODUCTION

During the last two decades, there has been a significant increase in LEO sun-synchronous missions for various applications (Dittberner and McKnight, 1993; Anilkumar and Sudheer Reddy, 2009). Regarding near-future activities, Petersen (1994), in his book *The road to 2015,* says: "most of the new growth in commercial space appears to be in LEO missions". An inherent characteristic of LEO missions is that the pattern of ground segment access to the satellite is made up by short and discontinuous access events (Wertz and Larson, 1999). To take account of this peculiar access pattern, in our previous papers (Bonyan Khamseh and Navabi, 2010a; 2010b) we developed two access-based metrics namely Total Accessibility Duration (TAD) and Longest Accessibility Gap (LAG). Accessibility gaps indicate requirement of autonomous operation (Chester, 2009) and in Bonyan Khamseh and Navabi (2010b) it was discussed that LAG metric is related to minimum requirement of in-orbit autonomy. To obtain LAG metric in a time-independent manner, the concept of repeatability cycle is employed. For a given repeatability cycle, it is discussed that longitude variation of a ground segment has negligible effect on LAG metric. Yet, our simulation results show that increasing the latitude of ground segment location improves LAG metric. It was observed that significant improvement in LAG metric is only achieved for very-high-latitude ground segments, at either Polar Regions. Still, establishment, operations and maintenance of ground segments at Polar Regions brings in practical difficulties. Thus, effectiveness of single-ground-segment architecture is questionable. To overcome this drawback, mission architectures with two ground segments are proposed and a procedure is given to select ground segments location with improved LAG metric.

The contribution of this paper is to improve LAG metric for LEO sun-synchronous missions by employing ground segment site location. In this manner, single and two-ground-segment architectures are studied.

NUMERICAL METHOD OF LAG DETERMINATION

Accessibility gap is defined as the time gap between any two consecutive events of ground segment access to the satellite, schematically shown in Fig. 1.

Thus, to obtain accessibility gaps in a given satellite mission, pattern of ground segment access to the satellite must be determined. For that purpose, position of the satellite in its orbit must be found. In our previous work (Bonyan Khamseh and Navabi, 2010b), Cowell's differential propagation formula was employed to obtain position of the satellite. In this paper, we employ some alternative analytical

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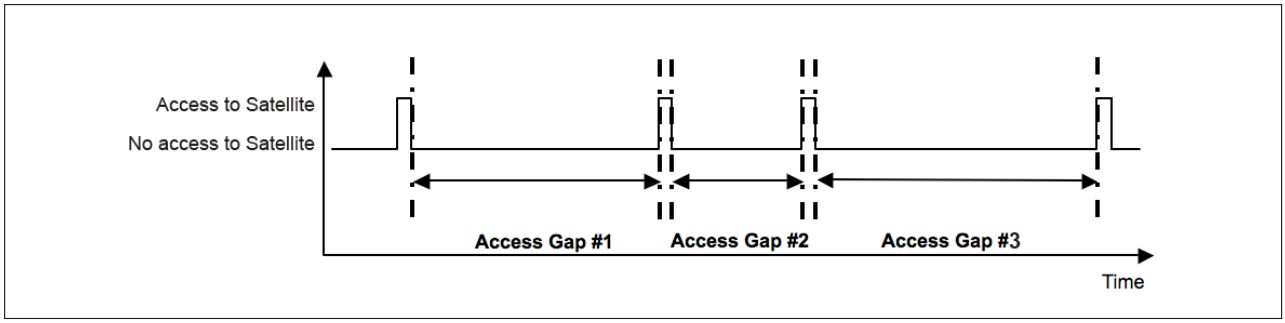


Figure 1: Gaps in ground segment access to a satellite.

relationships to obtain position vector of the satellite. In this method, Lagrange planetary equations are employed with the second-degree gravitational potential function. Lagrange planetary equations can be found in references such as Capderou (2005) and are given by Eq. 1:

$$\begin{cases} \dfrac{da}{dt} = \dfrac{1}{na}\left(2\dfrac{\partial R}{\partial M}\right) \\ \dfrac{de}{dt} = \dfrac{1}{na^2}\dfrac{1-e^2}{e}\left(-\dfrac{1}{\sqrt{1-e^2}}\dfrac{\partial R}{\partial \omega}+\dfrac{\partial R}{\partial M}\right) \\ \dfrac{di}{dt} = \dfrac{1}{na^2\sqrt{1-e^2}\,sin\,i}\left(-\dfrac{\partial R}{\partial \Omega}+cos\,i\dfrac{\partial R}{\partial \omega}\right) \\ \dfrac{d\Omega}{dt} = \dfrac{1}{na^2\sqrt{1-e^2}\,sin\,i}\left(\dfrac{\partial R}{\partial i}\right) \\ \dfrac{d\omega}{dt} = \dfrac{1}{na^2\sqrt{1-e^2}}\left(\dfrac{1-e^2}{e}\dfrac{\partial R}{\partial e}-\dfrac{cos\,i}{sin\,i}\dfrac{\partial R}{\partial i}\right) \\ \dfrac{dM}{dt} = n+\dfrac{1}{na^2}\left(-2a\dfrac{\partial R}{\partial a}-\dfrac{1-e^2}{e}\dfrac{\partial R}{\partial e}\right) \end{cases} \quad (1)$$

In Eq. 1, $\{a,e,i,\Omega,\omega,M\}$ is the Keplerian set of orbital elements namely semi-major axis, eccentricity, inclination, Right Ascension of Ascending Node (RAAN), argument of perigee and mean anomaly, respectively. Also $n=\sqrt{\frac{\mu}{a^3}}$ is the mean motion, μ is Earth gravitational parameter and R is perturbing Geopotential. A second-degree perturbing Geopotential takes account of J_2 effect i.e. dominant perturbation of LEO region and thus is employed in this study. If we only take account of the secular variations of orbital elements, we may obtain an elegant relationship for the average second-degree gravitational perturbing function, i.e. $\overline{R}_{J_2}$. The procedure to obtain $\overline{R}_{J_2}$ is given by Capderou (2005) and the result is given by Eq. 2:

$$\overline{R}_{J_2} = -\frac{3}{2}\frac{\mu R_e^2}{a^3\left(1-e^2\right)^{\frac{3}{2}}}J_2\left(\frac{1}{2}\sin^2 i-\frac{1}{3}\right) \quad (2)$$

Where R_e is Earth's equatorial radius and $J_2 = 0.00108263$ is a constant related to Earth's oblateness. Substituting Eq. 2 in Eq. 1 and noting that

$$\frac{\partial \overline{R}_{J_2}}{\partial a} = -\frac{3}{a}\overline{R}_{J_2},\ \frac{\partial \overline{R}_{J_2}}{\partial e} = -\frac{3e}{1-e^2}\overline{R}_{J_2},\ \frac{\partial \overline{R}_{J_2}}{\partial i} = \frac{\sin i\cos i}{\frac{1}{2}\sin^2 i-\frac{1}{s}}\overline{R}_{J_2}$$

and $\dfrac{\partial \overline{R}_{J_2}}{\partial M} = \dfrac{\partial \overline{R}_{J_2}}{\partial \omega} = \dfrac{\partial \overline{R}_{J_2}}{\partial \Omega} = 0$, we obtain the following analytical relationships for orbital elements of the satellite:

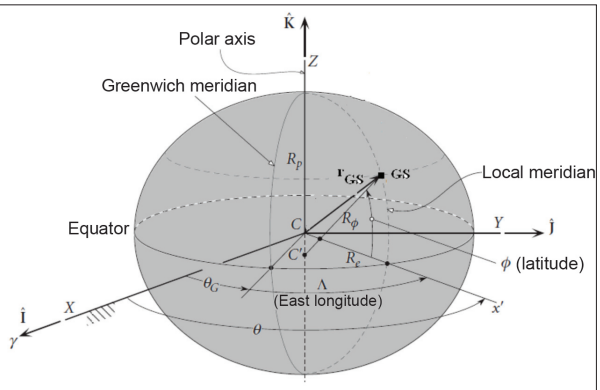
$$\begin{cases} \dot{a}=0 \rightarrow a(t)=a_0=cte \\ \dot{e}=0 \rightarrow e(t)=e_0=cte \\ \dot{i}=0 \rightarrow i(t)=i_0=cte \\ \Omega(t)=\Omega_0-\left[\dfrac{3}{2(1-e^2)^2}nJ_2\left(\dfrac{R_e}{a}\right)^2\cos i\right]\left(t-t_0\right) \\ \omega(t)=\omega_0+\left[\dfrac{3}{4(1-e^2)^2}nJ_2\left(\dfrac{R_e}{a}\right)^2\left(5\cos^2 i-1\right)\right]\left(t-t_0\right) \\ M(t)=M_0+\overline{n}(t-t_0) \end{cases} \quad (3)$$

Where $\overline{n}=\dot{M}=n_0\left[1+\dfrac{3}{4(1-e^2)^{\frac{3}{2}}}J_2\left(\dfrac{R_e}{a}\right)^2\left(3\cos^2 i-1\right)\right]$. With the orbital elements determined at any time t, satellite position, i.e. $\vec{r}_S$, may be determined in the geocentric inertial frame as:

$$\vec{r}_S(t)=\frac{a(1-e^2)}{1+e\cos\vartheta(t)}\begin{bmatrix} \cos\Omega\cos\omega-\sin\Omega\sin\omega\cos i & -\cos\Omega\sin\omega-\sin\Omega\cos\omega\cos i & \sin\Omega\sin i \\ \sin\Omega\cos\omega+\cos\Omega\sin\omega\cos i & -\sin\Omega\sin\omega+\cos\Omega\cos\omega\cos i & -\cos\Omega\sin i \\ \sin i\sin\omega & \sin i\cos\omega & \cos i \end{bmatrix}\begin{bmatrix} \cos\vartheta(t) \\ \sin\vartheta(t) \\ 0 \end{bmatrix} \quad (4)$$

And ϑ(t), i.e. satellite true anomaly, is determined from Kepler's equation by iterative methods such as Newton-Raphson. In case of circular orbits, simply ϑ(t)=M(t). With the satellite position determined at any time t, now ground segment position vector in the inertial frame must be determined. Based on WGS84 model, Fig. 2 shows a

ground segment (GS) on the Earth's surface in the inertial geocentric equatorial frame.



r_{GS}: ground segment position; θ: local sidereal time of ground segment (in degrees); R*e*: Earth's equatorial radius; Rϕ: radius of curvature in prime vertical (Polar axis); R*p*: Earth's polar radius; θ_G: Greenwich sidereal time (in degrees).

Figure 2: A ground segment (GS) on the surface of oblate Earth.

At a given time *t*, the ground segment position vector $\vec{r}_{GS}(t)$ in the inertial frame is given by:

$$\vec{r}_{GS}(t) = \begin{pmatrix} R_c \cos\varphi \cos\theta(t) \\ R_c \cos\varphi \sin\theta(t) \\ R_S \sin\varphi \end{pmatrix} \tag{5}$$

Where φ is ground segment latitude, $R_c = R_\varphi + Alt_{GS}$, $R_S = (1-f)^2 R_\varphi$, $R_\varphi = \frac{R_e}{\sqrt{1-(2f-f^2)\sin^2\varphi}}$ and f = 0.00335 is the Earth flattening factor. Also, Alt_{GS} is the altitude of ground segment above the ellipsoidal surface and θ (*t*) is the instantaneous angular distance between the ground segment location and the Vernal Equinox, measured in the equatorial plane. With $\vec{r}_{GS}(t)$ determined, position vector of the satellite relative to the ground segment $\vec{r}_{S\_rel\_GS}(t)$ is:

$$\vec{r}_{S\_rel\_GS}(t) = \vec{r}_S(t) - \vec{r}_{GS}(t) \tag{6}$$

At any given time, the satellite is accessible from the ground segment if Eq. 7 is satisfied:

$$\varepsilon(t) = 90 - \cos^{-1}\left(\frac{\vec{r}_{S\_rel\_GS}(t)\cdot\vec{r}_{GS}(t)}{r_{S\_rel\_GS}(t) * r_{GS}}\right) \geq \varepsilon_{\min} \tag{7}$$

In Eq. 7, $\vec{r}_{S\_rel\_GS}(t)$ and r_{GS} are magnitudes of $\vec{r}_{S\_rel\_GS}(t)$ and $\vec{r}_{GS}(t)$, respectively. ε_{min} accounts for minimum ground elevation constraint, typically 5-10 degrees for commercial communication hardware. From Eq. 7, rise/set times of the satellite with respect to a given ground segment may be determined. Duration of each accessibility gap is computed by subtracting the access termination time from next access initiation time.

LAG – MINIMUM TIME INTERVAL TO STUDY?

In LEO missions, chronological distribution of the ground segment access to the satellite varies as the time interval of study is increased. This brings up an immediate drawback since, in this manner, LAG will be a time-dependent metric. Yet, after a certain simulation time, it is observed that distribution of access events repeats identically. This time interval is called repeatability cycle and is taken as the minimum time interval to obtain time-independent LAG metric. For a satellite mission with given orbit, one may obtain repeatability cycle, i.e. *D*, from Eq. 8:

$$D = \frac{Rev * (\omega_e - \dot{\Omega})}{n + \Delta n + \dot{\omega}} \tag{8}$$

Where *Rev* is integer number of full revolution in *D* days, and $\omega_e = 7.2925 * 10^{-5} rad/\text{sec}$ is Earth's rotation rate. For sun-synchronous orbits, we have $\dot{\Omega} = 1.9965 * 10^{-7}$ rad/sec . Also, Δ*n* and $\dot{\omega}$ are:

$$\Delta n = \frac{3}{4(1-e^2)^{\frac{3}{2}}} n J_2 \left(\frac{R_e}{a}\right)^2 \left(3\cos^2 i - 1\right)$$

$$\dot{\omega} = \frac{3}{4(1-e^2)^2} n J_2 \left(\frac{R_e}{a}\right)^2 \left(5\cos^2 i - 1\right)$$

In Eq. 8, only integer values of *D* give admissible scenarios. Chronological distribution of access events is identical after each *D* days and, consecutively, LAG metric is determined in a time-independent manner. Thus, repeatability cycle obtained from Eq. 8 is taken as the time interval to study LAG metric.

SITE LOCATION OF GROUND SEGMENT

As it was discussed in the section "Numerical method of LAG determination", for a mission with given orbit, LAG metric depends on the ground segment location. In this section, selection of ground segment location is employed as a mechanism to improve LAG metric.

Site location of single ground segment

Location of a ground segment on the terrestrial surface is given by three parameters, namely longitude, latitude and

altitude relative to the mean surface level. In this paper, effect of longitude and latitude of the ground segment on LAG metric is studied and zero altitude is assumed for all ground segment locations.

Effect of ground segment longitude

Through extensive simulations for given repeatability cycles, it was observed that pattern of access to LEO sun-synchronous satellite remains constant as the location of ground segment is altered in the longitude direction. In Li and Liu (2002), it was analytically shown that the Probability Density Function (PDF) of elevation angles for a given ground segment does not depend on its longitude. Also, the same results were verified by extensive simulations in Modiri and Mohammady (2008). Consequently, selection of ground segment location to reduce LAG metric must be done in the latitude direction, only.

Effect of ground segment latitude

Based on the results obtained in Li and Liu (2002), the PDF of elevation angles is symmetrical for both northern and southern hemispheres. Thus, for two ground segments at latitude of ± *lat*, identical access patterns and LAG metrics are obtained. Due to the fact that most of the lands at the terrestrial surface reside in the northern hemisphere, one may assume that the ground segment resides in northern hemisphere. Latitude of the ground segment is changed from Equator to 90° N i.e. North Pole. Step size for latitude variation may be chosen according to the required accuracy. Here we will adopt 10 *deg* steps, in northward direction.

Site location of two ground segments

To achieve further improvement in LAG metric, two-ground-segment mission architectures are discussed in this section. We will assume co-latitude ground segments. From previous subsections, longitude of either ground segments has negligible effect on LAG metric. Thus, at constant latitude, only the relative longitude distance between the two ground segments must be selected.

In two-ground-segment mission architectures, care must be taken to merge access patterns of two ground segments in order to obtain the combined network access pattern. In general, sequential access pattern of a two-ground-segment network to a satellite may take any of the five types shown in Fig. 3. In access type (a), the ground segments access to the satellite do not overlap at all. In access types (b) and (c), the ground segments access to the satellite partially overlap each other. Finally, in access types (d) and (e), a ground segment access to the satellite initiates before and extends after the other ground segment access to the satellite. Regarding these five access types, single ground segment access events must be merged accordingly to obtain the network access pattern.

In the next section, a case study is discussed to evaluate the effect of ground segment(s) location on LAG metric.

SIMULATION AND RESULTS

To evaluate the effect of ground segment site location on LAG metric in a given LEO sun-synchronous mission, a case study is considered. Orbital parameters of our case study – called RS-Sat hereafter – are shown in Table 1.

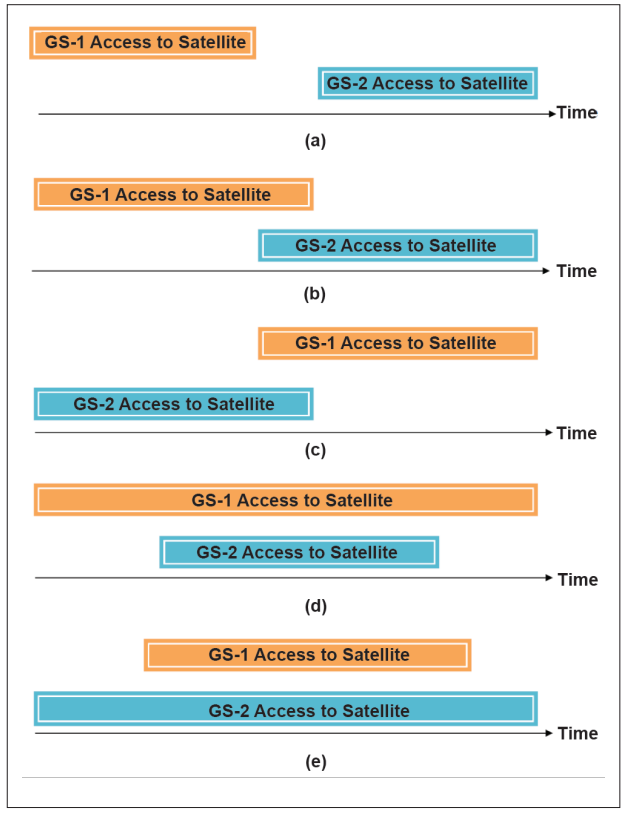


Figure 3: Possible sequential types of two ground segments access to a satellite.

Table 1: Orbital characteristics of RS-Sat

Parameter	Value
Orbit altitude	655 km
Eccentricity	0
Inclination	98.01 deg (sun-synchronous)
Local time of ascending node	10:00 a.m.

Orbital altitude of 655 km has been selected to reflect the popularity of the 600-1,000 km range for remote sensing applications (Stephens, 2002; Sandau, 2010). Similarly, local time of ascending node of 10:00 a.m. has been purposefully adopted to reflect the popularity of such architecture for imagery purposes (Stephens, 2002). From Eq. 8, repeatability cycle of RS-Sat is 10 days. Thus, simulation was carried out for a 10-day period from 1 Jan 2010 00:00:00 to 10 Jan 2010 24:00:00. Just as in the case of preceding parameters, a 10-day period reflects the upper-bound of revisit-time requirements for various remote sensing applications (Stephens, 2002).

Single ground segment scenarios

In the first scenario, the ground segment resides at the Equator and the arbitrary longitude of 30° N. In subsequent scenarios, latitude of ground segment is increased in 10 *deg* steps. By this reasoning, location of the ground segment in the tenth scenario will be in 30° E 90° N, i.e. in the center of the arctic region. For the 10-day simulation period, LAG metric in each scenario was obtained and illustrated in Fig. 4, in which it can be readily seen that very little improvement in LAG metric is obtained as the ground segment moves from the Equator to the latitude of 50° N. At the latitude interval of 60° N–70° N, LAG metric experiences additional improvement. Significant improvement in LAG metric is achieved only in the 70° N - 90° N latitude interval, especially in the upper-bound limits, i.e. the arctic region. However, due to adverse environmental conditions and poor access to required operational resources (e.g. electricity) at affordable cost, Polar Regions are highly disadvantageous for ground segment deployment. As a result, effectiveness of single-ground-segment architecture is questionable.

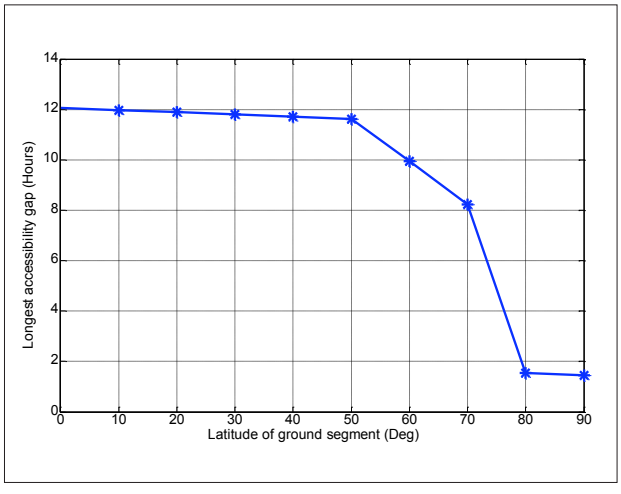


Figure 4: Longest accessibility gap metric for RS-Sat in single ground segment scenarios.

Two-ground-segment scenarios

To achieve further improvement in LAG metric, two-ground-segment mission architectures are explored in this section. To avoid difficulties encountered in Polar Regions, we will assume 60° N as the upper latitude limit for ground segments location. Co-latitude ground segments at 60° N are considered. From previous subsections, longitude of either ground segments has negligible effect on LAG metric. In the first scenario, location of the first and second ground segment will be considered at 30° E 60° N and 40° E 60º N, respectively i.e. a 10º difference in longitude direction. In the subsequent scenarios, longitude difference will be increased in 10° steps in the eastward direction. Thus, the longitude distance between the two ground segments in j^{th} scenario i.e. ΔL_j is (Eq. 9):

$$\Delta L_j = j*10 \tag{9}$$

where j is the sequential number of the scenario. The 10° increment in longitude difference between the two ground segments will result in 35 scenarios. Due to circular cross section of the Earth, only 18 unique two-ground-segment scenarios are taken into account. For the 10-day repeatability cycle, simulations were carried out for the 18 described scenarios and pattern of two-ground-segment network access to RS-Sat was obtained for each scenario. Results for LAG metric for each scenario are given in Fig. 5.

As it can be seen from Fig. 5, minimum LAG is experienced in the 12th scenario, in which the ground segments reside at 30° E 60° N and 150° E 60° N, i.e. 120° apart in the longitude direction. In this scenario, LAG metric is 11549 seconds, i.e. 3 hours 12 minutes and 29 seconds. At this point, it must be verified that lands 120° apart in the longitude direction actually exist at the latitude of 60° N over the Earth's surface (for practical applications, the two ground segments must reside on land not in the seas!). If the preferred two-ground-segment architecture did not fit into the land distribution over the terrestrial surface, the scenario with second-best LAG metric would be examined, and so on.

It is recalled that if it was desired to achieve the same LAG metric i.e. 11549 seconds by single ground segment architecture, latitude of the ground segment would be 77.5° N somewhere in the arctic regions. This verifies the effectiveness of the two-ground-segment architecture to improve LAG metric while avoiding operational difficulties of ground segments in very-high latitudes and the arctic region.

CONCLUSION

LAG is an important metric which is related to minimum requirement of in-orbit autonomy. An analytical approach was adopted to determine the prescribed metric. Site selection of single and two ground segments to improve LAG metric

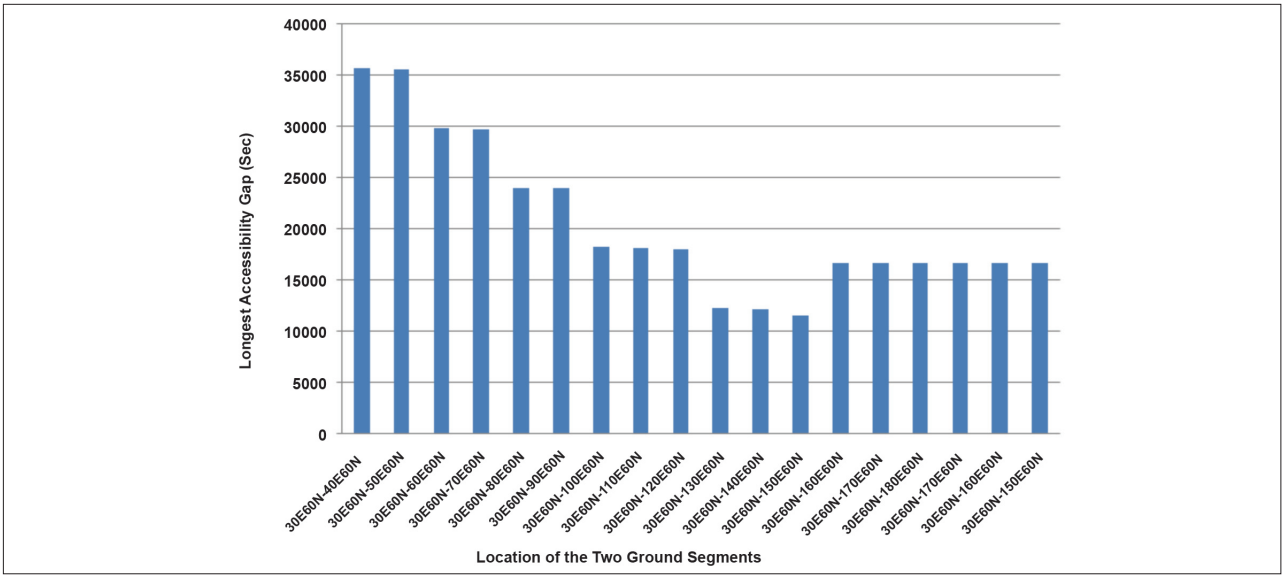


Figure 5: Longest accessibility gap metric for RS-Sat in two-ground-segment scenarios.

in LEO sun-synchronous missions was discussed. Our results showed that, for single ground segment, LAG metric improves as the ground segment moves to high latitudes and Polar Regions. Also, for two-ground-segment mission architectures, the relative distance to achieve improved LAG metric was obtained. It was observed that two-ground-segment mission architectures are effective in that they offer improved LAG metric while avoiding operational difficulties of polar ground segments. By employing the procedures discussed in this paper, one may determine single and two-ground-segment architectures to provide acceptable LAG metric in a given mission.

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