Space Based Data Centers – Communication Window Length Analysis from an African Perspective

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Abstract – The use of space based data centers (SDBCs) is beneficial for realizing future environment-friendly networks. This is because they do not require the use of earth's water resources for cooling. In addition, SBDCs are important entities in future networks. This is because they are able to provide content access to subscribers in landlocked and disaster prone locations with low access to conventional terrestrial data centers. The research recognizes the importance of the SBDC uptime that should be considered alongside the use of SBDCs. The research aims to analyze the uptime of SBDCs via the consideration of the communication window length considering different ground locations. The ground locations considered have high susceptibility to seismic events and are hosted in Africa. Research shows that a minimum and maximum SBDC uptime are 419.4 minutes, and 435.6 minutes for select African landlocked countries, respectively. The minimum and maximum SBDC uptime are 329.6 minutes, and 435.6 minutes for select African seismic event prone countries, respectively.

Keywords – space based data centers, communication window length, Africa, Seismic prone regions.

I. INTRODUCTION

Data centers play a significant role in computing and communication networks. They host content that is stored and accessible by subscribers to mobile networks. Conventionally, a considerable number of data centers are hosted in earth's terrestrial environment. The terrestrial data centers concerned have been recognized to have non-environment friendly operation. These has necessitated research to realize future green data centers [1– 3].

The need to realize environment-friendly and energy efficient data centers has necessitated the design of non-terrestrial data centers. In this case, non-terrestrial data centers can be sited in the stratosphere environment [4–6], and space environments [7–10]. The siting of data centers in these environments has the benefits of using cooling methods that do not use earth's water resources.

The use of space based data centers has received initial application and some research attention. In addition, space based data centers have been recognized as an emerging technology by the European Union in the ASCEND initiative [11].

Being non-terrestrial, space based data centers (SBDCs) are also suitable for regions that are landlocked. Landlocked regions have significant limitations in hosting terrestrial data centers due to the paucity of significant water resources. The limitation of water resource availability limits water use in data center cooling.

Stratosphere based data centers can be used in such regions as they rely on stratosphere radiative cooling. However, the use of stratosphere based data centers requires significant infrastructure development. For example, airport like facilities is required to launch stratosphere platforms and enable their landing for maintenance. Besides the launch enabled by the space port, similar landing facilities are not required for space based data centers.

However, the use of space based data centers requires an analysis of their communication duration. The communication duration i.e., length of communication window is important for select landlocked African countries. The communication window is an epoch (data transmission opportunity) where orbiting space based data centers communicate with an earth based terrestrial ground station. The length of the communication window is given in seconds. In addition, it is important to examine the length of the communication window for African countries that are prone to seismic events. The conduct of such an analysis aims to describe the communication capabilities of SBDCs for African countries. The concerned African countries are considered in two tiers. In the first tier, landlocked African countries are considered. The concerned countries in this case are: (i) Burundi, (ii) Chad, (iii) Ethiopia, (iv) South Sudan, and (v) Rwanda. The second tier considers African countries that are prone to Seismic events. The considered countries in this regard are: (i) Ethiopia [12], (ii) South Africa [13], and (iii) Eritrea [14].

The major contribution of the research is the analysis of SBDC's communication window length. The hypothesis is that the use of SBDCs can enable communications with varying data transmission duration in African landlocked regions and locations that are prone to seismic events. Such locations pose significant threats to terrestrial data center facilities. In this case, SBDC space assets are in the medium earth orbit. The low earth orbit has not been considered due to its high orbital congestion. This is done with focus on the African continent. The conduct of such an analysis is deemed important. It serves as a basis for determining the feasibility of developing SBDCs. The analysis of the

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communication window length is done using the MATLAB Orbit Propagator Toolbox. The conducted and presented analysis is deemed relevant and important for network

The rest of the research is organized as follows. Section II discusses the manner of the determination of orbital parameters. Section III presents the evaluation of the communication window length for landlocked African countries. Section IV focuses on the evaluation of the communication window length for the seismic-event prone African countries. Section V is the conclusion of the research. Section VI evaluates and describes the performance benefit. Section VI concludes the research.

II. ORBITAL PARAMETERS DETERMINATION

The orbital parameters to be determined in this case are: (i) Semi-major axis, (ii) Eccentricity, (iii) Inclination, (iv) Right ascension of the ascending node for a given position vector, and velocity vector, (v) Argument of periapsis, (vi) argument of latitude, (vii) True Anomaly, (viii) Mean Anomaly, and (ix) Longitude of periapsis.

The parameters listed above are determined in the following manner [15]. The semi-major axis a is determined by the sum of the satellite altitude r and radius of the earth R_E as:

$$a = r + R_E \tag{1}$$

In the paper, a circular orbit is considered. For a circular orbit, the eccentricity, e is zero i.e., $e = 0$. Therefore, the eccentric anomaly, true anomaly, and mean anomaly are zero. The motivation for considering that SBDCs are deployed in a circular orbit: (i) energy efficiency due to low variations in satellite velocity and orbital altitude, (ii) low signal variability leading to consistent coverage and excellent signal communication ability, (iii) low computational cost and orbital predictability.
Furthermore, the inclination i is given as:

$$i = Lat + \theta \tag{2}$$

Lat is the latitude of the location.
θ is the angular increment such that $\theta > Lat$.

The right ascension of the ascending node is determined the position vector r, and the velocity vector v of the satellite.

$$r = (r_x, r_y, r_z) \tag{3}$$

$$v = (v_x, v_y, v_z) \tag{4}$$

The satellite position i.e., altitude is derived as the magnitude of r, r_{pos} given as:

$$r_{pos} = \sqrt{r_x^2 + r_y^2 + r_z^2} \tag{5}$$

The satellite velocity is derived as the magnitude of v, v_{pos} given as:

$$v_{pos} = \sqrt{v_x^2 + v_y^2 + v_z^2} \tag{6}$$

The angular momentum vector h is determined as the cross product of the position vector and the velocity vector as:

$$h = r \times v \tag{7}$$

The node vector, N is also required to determne the right ascension of the ascending node, and is given as:

$$N = k \times h \tag{8}$$

The node vector N has three components and is given as:

$$N = (N_x, N_y, N_z) \tag{9}$$

The right ascension of the ascending node, Ω is given as:

$$\Omega = cos^{-1}\left(\frac{N_x}{\sqrt{N_x^2 + N_y^2 + N_z^2}}\right) \tag{10}$$

Argument of periapsis, ω, is influenced by the eccentricity vector, e given as:

$$e = \frac{1}{398600}\left(v_{pos}^2 - \frac{398600}{r_{pos}^2}\right) r - (r.v)v \tag{11}$$

$$\omega = cos^{-1}\left(\frac{N.e}{|N|\,|e|}\right) \tag{12}$$

$|N|$, and $|e|$ are the magnitude of the node vector, and eccentricity vector, respectively.

The argument of latitude, L is given as:

$$L = \omega + \text{True Anomaly} \tag{13}$$

Longitude of periapsis, P is given as:

$$P = \Omega + \omega \tag{14}$$

In the presented analysis, the networking architecture has an SBDC utilizing high speed radio frequency links or free space optical links for communicating with the ground station. The use of high speed links in the proposed manner enables the realization of high speed terabit per second link capacity. Such link is preferrable as seen in [16 – 20]. The concerned link capacity is applicable to SBDCs delivering data in landlocked countries, and for seismic event prone countries.

III. LANDLOCKED COUNTRIES – WINDOWS

The discussion in this section presents the communication windows for selected African landlocked countries. The concerned countries in this case are: (i) Burundi, (ii) Chad, (iii) Ethiopia, (iv) South Sudan, and (v) Rwanda. In the consideration, a ground station is placed at the capital of each of the countries concerned. The capital of Chad, Ethiopia, South Sudan and Rwanda are N'Djamena (12.1348° N, 15.0557° E), Gitega (3.4284° S, 29.9246° E.), Juba (4.8594° N, 31.5713° E.), and Kigali (1.9706° S, 30.1044° E.).

The communication window is evaluated in the context of a positive link margin. A positive link margin enables the realization of effective communication given challenging atmospheric conditions. The SBDC being considered is hosted in the medium earth orbit with reduced exposure to orbiting space debris in comparison to low

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earth orbit. Hence, SBDC operation is assumed without exposure to space debris. In addition, SBDC design, deployment and use has emerged after the execution of a standard space mission and analysis procedure.

The communication window for each of the concerned locations is determined using the MATLAB Orbit Propagator object oriented framework. The evaluation of the communication window is considered given that each country launches own SBDC in the medium earth orbit. The medium earth orbit is considered due to the orbital congestion in the low earth orbit. In all cases the SBDC position vector is given as (4800 km, 7800 km, 6805 km). In a comparable manner, the SBDC velocity vector is given as (5970km/s, 5300km/s, 5500km/s). The evaluation parameters for N'djamena, Gitega, Juba and Kigali are presented in Table 1. The orbital scenario enabling the determination of the window access epochs is in Figure 1. The scenario in Figure 1 is the satellite scenario viewer and obtained from the MATLAB Orbit Propagator interface.

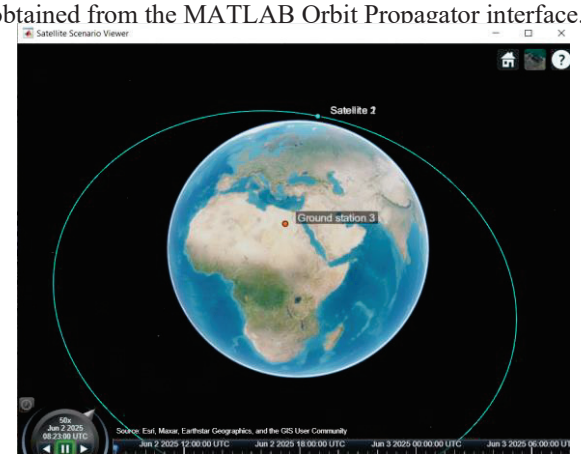

Figure 1: Satellite (Satellite 2–SBDC) and Ground Station (Ground Station 3) evaluation obtained from the MATLAB Satellite Scenario Viewer.

The SBDC communication windows with the ground station at Ndjamena, Gitega, Juba and Kigali are presented in Figure 2, Figure 3, Figure 4, and Figure 5, respectively. The results in Figures 2, 3, 4, and 5 show that the selected landlocked country locations have varying communication window profiles and associated durations. This enables the verification of the research hypothesis regarding the asymmetry of communication window for the considered locations.

Table 1: Communication Window Evaluation Parameters

Parameter	N'djamena	Gitega	Juba	Kigali
Altitude	11410km	11410km	11410km	11410km
Velocity	9694km/s	9694km/s	9694km/s	9694km/s
i	21.885 deg	13.178 deg	14.609 deg	11.721 deg
Ω	154.34 deg	154.34 deg	154.34 deg	154.34 deg
ω	71.44 deg	71.44 deg	71.44 deg	71.44 deg
L	71.44 deg	71.44 deg	71.44 deg	71.44 deg
P	225.78 deg	225.78 deg	225.78 deg	225.78 deg

The results in Figure 2, Figure 3, Figure 4, and Figure 5 shows that each of the concerned locations in African landlocked countries has five communication windows. The analytic period in this case spans the dates June 02, 2025, to June 03, 2025. The choice of these dates is arbitrary. The coverage evaluation procedure shows that the number of windows remains the same for another arbitrary set of number of days. In addition, it is observed that there are a total of six communication windows for the considered epochs. Each of the six communication windows has a varying window length i.e., duration.

StartTime	EndTime	Durati
02-Jun-2025 09:38:42	02-Jun-2025 10:43:06	3864
02-Jun-2025 13:37:18	02-Jun-2025 14:45:48	4110
02-Jun-2025 17:28:12	02-Jun-2025 18:40:18	4326
02-Jun-2025 21:21:42	02-Jun-2025 22:34:00	4338
03-Jun-2025 01:16:06	03-Jun-2025 02:28:24	4338
03-Jun-2025 05:09:30	03-Jun-2025 06:19:18	4188

Figure 2: Communication Windows for N'Djamena (12.1348° N, 15.0557° E).

StartTime	EndTime	Duration
02-Jun-2025 09:45:54	02-Jun-2025 10:57:30	4296
02-Jun-2025 13:41:18	02-Jun-2025 14:53:48	4350
02-Jun-2025 17:35:36	02-Jun-2025 18:48:18	4362
02-Jun-2025 21:31:18	02-Jun-2025 22:43:54	4356
03-Jun-2025 01:26:18	03-Jun-2025 02:39:06	4368
03-Jun-2025 05:21:06	03-Jun-2025 06:33:18	4332

Figure 3: Communication Windows for Gitega (3.4284° S, 29.9246° E.).

StartTime	EndTime	Duration
02-Jun-2025 09:47:30	02-Jun-2025 10:58:24	4254
02-Jun-2025 13:42:54	02-Jun-2025 14:55:12	4338
02-Jun-2025 17:36:42	02-Jun-2025 18:49:30	4368
02-Jun-2025 21:32:24	02-Jun-2025 22:44:54	4350
03-Jun-2025 01:27:12	03-Jun-2025 02:39:54	4362
03-Jun-2025 05:22:06	03-Jun-2025 06:33:48	4302

Figure 4: Communication Windows for Juba (4.8594° N, 31.5713° E.).

StartTime	EndTime	Duration
02-Jun-2025 09:45:36	02-Jun-2025 10:57:42	4326
02-Jun-2025 13:41:00	02-Jun-2025 14:53:42	4362
02-Jun-2025 17:35:36	02-Jun-2025 18:48:24	4368
02-Jun-2025 21:31:24	02-Jun-2025 22:44:00	4356
03-Jun-2025 01:26:30	03-Jun-2025 02:39:24	4374
03-Jun-2025 05:21:24	03-Jun-2025 06:33:54	4350

Figure 5: Communication Windows for Kigali (1.9706° S, 30.1044° E.).

In the case of N'Djamena, the least communication window length is 3864 seconds (64.4 minutes). The maximum communication window length is 4338 seconds (72.3 minutes). In this case, the average communication window length is 4194 seconds (69.6 minutes).

The least communication window length for Gitega is 4296 seconds (71.6 minutes). In an analogous manner, the

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maximum communication window length is 4368 seconds (72.8 minutes). In this case, the average communication window length is 4344 seconds (72.4 minutes). In the case of Juba, the least communication window length is 4254 seconds (70.9 minutes). The maximum communication window length is 4368 seconds (72.8 minutes). The computed mean communication window length is evaluated as 4329 seconds (72.15 minutes).

In addition, the minimum obtainable communication window length for Kigali is observed to be 4326 seconds (72.1 minutes). The maximum obtainable communication window length is observed to be 4374 seconds (72.9 minutes). In addition, the mean communication window length obtained for Kigali via the evaluation procedure is given by 4356 seconds (72.6 minutes).

From the presented analysis, the location with the best ommunication window profile is Kigali. Kigali has a minimum, mean and maximum communication window length of 72.1 minutes, 72.6 minutes, and 72.9 minutes, respectively. The location with the least performance communication window profile is N'Djamena with the minimum, mean and maximum communication window length of 64.4 minutes, 69.6 minutes, and 72.3 minutes, respectively.

In addition, it can be seen that the communication window profile exceeds an hour with the least being 64.4 minutes. Therefore, data upload or download can take place for periods exceeding 45 minutes. Given an effective link speed of 40 Gbps and a communication latency of 40 ms, the amount of data that can be transmitted in a 10 minute duration is 3000 GB (3 TB). Therefore, a total data size of 9 TB can be estimated to be transmitted in a 30 minute period. This data size is appreciable. Therefore, the role of the SBDC at the concerned locations has value.

Given that the communication window profile is presented in the format (minimum, mean, maximum). The communication window profile of Juba (70.9 minutes, 72.15 minutes, 72.8 minutes) is observed to be better than that of Gitega (71.6 minutes, 72.4 minutes, 72.8 minutes). Therefore, the rank of communication window based on the considered locations in ascending order is given as: N'Djamena (64.4 minutes, 69.6 minutes, 72.3 minutes) ; Gitega (71.6 minutes, 72.4 minutes, 72.8 minutes) ; Juba (70.9 minutes, 72.15 minutes, 72.8 minutes), and Kigali (72.1 minutes, 72.6 minutes, 72.9 minutes). In addition, the total communication window length for N'Djamena, Gitega, Juba and Kigali are 25,164 seconds (419.4 minutes), 26,064 seconds (434.4 minutes), 25,974 seconds (432.9 minutes), and 26,136 seconds (435.6 minutes).

Furthermore, it can be seen that there are gaps between communication epochs for each of the concerned locations. The presence of a communication gap and a single orbiting SBDC implies reduced power consumption. This is beneficial and ensures that the operation of the ground station does not constitute significant load on the grid.

The evaluated total communication duration describes the SBDC uptime within the evaluation period of June 02, 2025, to June 03, 2025. It can be seen that the SBDC uptime achieved in this period is less than that of the conventionally used terrestrial data center. The least and maximum SBDC uptime are 419.4 minutes (N'Djamena), and 435.6 minutes (Kigali), respectively. Nevertheless, it should be noted that the use of the SBDC has the benefits of ensuring zero water footprint in these landlocked locations. The SBDC has a zero water footprint because it does not rely on earth's water resources. Instead, it can be cooled using water resources mined from near earth orbiting asteroids.

Therefore, the use of multiple SBDCs or ground stations is most beneficial with increasing the number of coverage windows and communication window lengths for N'Djamena (Chad location). However, the evaluation considers the case that capital constraints arise in the concerned African landlocked locations. The occurrence of capital constraints in this case leads to the inability to deploy more SBDCs and ground stations.

IV. WINDOW IN SEISMIC PRONE COUNTRIES

The discussion in this section focuses on the evaluation and analysis of the communication windows for African countries prone to experience seismic events. The considered countries are Ethiopia, Eritrea, and South Africa. The capital locations and the coordinates for Ethiopia, Eritrea, and South Africa are given as Addis Ababa (9.03° N, 38.74° E), Asmara (15.33° N, 38.93° E), and Johannesburg (26.2044° S, 28.0456° E), respectively.

The SBDC for each of the locations concerned has a position vector of (4800 km, 7800 km, 6805 km). In addition, the SBDC velocity vector is given as (5970km/s, 5300km/s, 5500km/s). The evaluation parameters for Addis Ababa (AA), Asmara (AS), and Johannesburg (JHB) are presented in Table 2. The communication windows for the SBDC with the ground station at AA, AS and JHB are presented in Figure 6, Figure 7, and Figure 8, respectively. The results presented in this case enable the investigation of the research hypothesis related to examining the communication window for seismic event prone locations.

Table 2: Communication Window Evaluation Parameters

Parameter	AA	AS	JHB
Altitude	11410km	11410km	11410km
Velocity	9694km/s	9694km/s	9694km/s
i	18.78 deg	25.08 deg	43.67 deg
Ω	154.34 deg	154.34 deg	154.34 deg
ω	71.44 deg	71.44 deg	71.44 deg
L	71.44 deg	71.44 deg	71.44 deg
P	225.78 deg	225.78 deg	225.78 deg

The communication window results in this case aim to demonstrate the ability of the SBDC to provide data access in the locations concerned. In this case, the data access is executed via uplink and downlink. The data access is provided in a post-disaster scenario and context. In this case, the occurrence of seismic related disasters impairs the availability of conventional terrestrial computing platforms. Therefore, the usefulness of terrestrial computing platforms such as terrestrial large-scale data centers, terrestrial edge nodes and terrestrial modular data centres have become limited. The analysis and discussion of the communication window length is examined from the perspective of providing post-disaster communications.

An analysis of the results presented in Figure 6, Figure 7, and Figure 8 shows that there are five communication windows for the locations concerned of Addis Ababa, Asmara and Johannesburg. In the following discussion, the communication window profile is presented in the format (minimum communication window, mean communication window, maximum communication window).

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StartTime	EndTime	Duration
02-Jun-2025 09:54:48	02-Jun-2025 11:03:06	4098
02-Jun-2025 13:49:06	02-Jun-2025 15:00:42	4296
02-Jun-2025 17:41:48	02-Jun-2025 18:54:18	4350
02-Jun-2025 21:37:06	02-Jun-2025 22:49:36	4350
03-Jun-2025 01:31:00	03-Jun-2025 02:43:12	4332
03-Jun-2025 05:26:36	03-Jun-2025 06:36:00	4164

Figure 6: Communication Windows for Addis Ababa (9.03° N, 38.74° E).

StartTime	EndTime	Duration
02-Jun-2025 10:01:12	02-Jun-2025 11:02:06	3654
02-Jun-2025 13:53:00	02-Jun-2025 15:02:48	4188
02-Jun-2025 17:42:54	02-Jun-2025 18:55:06	4332
02-Jun-2025 21:37:06	02-Jun-2025 22:49:18	4332
03-Jun-2025 01:29:36	03-Jun-2025 02:40:42	4266
03-Jun-2025 05:26:00	03-Jun-2025 06:30:06	3846

Figure 7: Communication Windows for Asmara (15.33° N, 38.93° E).

StartTime	EndTime	Duration
02-Jun-2025 13:59:12	02-Jun-2025 15:01:18	3726
02-Jun-2025 17:40:12	02-Jun-2025 18:50:54	4242
02-Jun-2025 21:30:24	02-Jun-2025 22:41:48	4284
03-Jun-2025 01:20:18	03-Jun-2025 02:30:06	4188
03-Jun-2025 05:12:42	03-Jun-2025 06:08:18	3336

Figure 8: Communication Windows for Johannesburg (26.2044° S, 28.0456° E).

The communication window profile for Addis Ababa is (68.3 minutes, 71.1 minutes, 72.5 minutes). The communication window profile for Asmara is given as (60.9 minutes, 68.4 minutes, 72.2 minutes). The communication window profile for Johannesburg is given as (55.6 minutes, 65.9 minutes, 71.4 minutes). In this case, Johannesburg has a reduced number of communication windows with five communication windows.

Based on the number of communication windows, the SBDC has more communication epochs at Addis Ababa and Asmara than at Johannesburg. In addition, the rank of locations based on communication window profile in ascending order is Johannesburg (55.6 minutes, 65.9 minutes, 71.4 minutes), Asmara (60.9 minutes, 68.4 minutes, 72.2 minutes), and Addis Ababa (68.3 minutes, 71.1 minutes, 72.5 minutes). The total communication duration for Johannesburg, Asmara and Addis Ababa are 19,776 seconds (329.6 minutes), 24,618 seconds (410.9 minutes) and 25,590 seconds (426.5 minutes), respectively.

It can also be observed that the total communication duration, i.e., SBDC uptime is lower than that obtainable for conventional terrestrial data center systems. However, it is important to note that the terrestrial data center systems become non-functional given a seismic related event.

Furthermore, communication gaps can be observed to arise in the results presented in Figure 6, Figure 7, and Figure 8. The gap ensures that the ground station is not energy intensive in a post-disaster scenario. This has the benefit of ensuring that energy is available for other crucial applications in a post-disaster scenario.

V. CONCLUSION

The discussion in the presented research focuses on analyzing the communication window length and epochs for space based data centers (SBDCs). SBDCs are recognized as suitable candidates for computing platforms. This is because SBDCs have performance benefits of having zero earth water footprint and do not degrade environmental biodiversity. The analysis is done for the case of select African landlocked countries, and African countries that are prone to seismic events and natural disasters. In the case of landlocked countries, the selected states are Burundi, Chad, South Sudan and Rwanda. The selected seismic event prone countries are Ethiopia, Eritrea, and South Africa. The analysis of the communication window is done from a developmental perspective for the selected countries considered. The analytic scenario is one in which each of the countries considered launch only one SBDC and have one ground station. Such a scenario has been deemed beneficial from the perspective of reduced resources and ensuring development in a capital constrained context. Evaluation shows that a minimum and maximum SBDC uptime are 419.4 minutes, and 435.6 minutes for select African landlocked countries, respectively. The minimum and maximum SBDC uptime are 329.6 minutes, and 435.6 minutes for select African seismic event prone countries, respectively. The research presents results related to the communication window and profile associated with landlocked and seismic regions within Africa. The results presented enable the investigation of the research hypothesis on the asymmetry of communication windows for locations in these regions. From the results presented, it can be seen that SBDCs can be used instead of conventional terrestrial data centers with a varying and appreciable communication duration exceeding 2.5 hours from the analysis of the results obtained from MATLAB Orbit Propagator.

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