A COMPILATION OF MEASURED ADS-B PERFORMANCE CHARACTERISTICS FROM AIREON'S ON-ORBIT TEST PROGRAM

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Abstract

In just a few short years, space-based ADS-B has already transformed the roadmap for aircraft surveillance within the Air Traffic Management (ATM) industry. ADS-B (Automatic Dependent Surveillance – Broadcast) avionics is rapidly becoming mandatory aircraft equipage for many airspaces [1] [2]. ADS-B is ushering in a new era of flight tracking, surveillance, improved safety, and increased efficiency [3] [4]. Operational acceptance by Air Navigation Service Providers (ANSPs) of new technologies such as space-based ADS-B will depend in part on the outcomes of rigorous testing. Aireon conducted a series of on-orbit tests and characterizations to verify and validate key requirements and expectations of the system. The group of requirements with the highest priority for validation are known as the Technical Performance Metrics (TPMs) and are composed of Availability, Latency, and Update Interval.

Although initial results with a handful of payloads were shared in prior publications [5, 6], this paper will discuss results observed with 55 out of 66 payloads receiving ADS-B data. In addition, various constraints were removed from the system over time, leading to gradual improvements in all TPMs. Furthermore, certain classes of ADS-B transmitters (e.g. bottom-only antenna aircraft) were analyzed in isolation to better understand their performance profiles versus the general air transport population. The results contained in this work should help illuminate the key current capabilities of the Aireon system as well as the remaining expectations left to be demonstrated at the completion of formal Service Acceptance Testing (SACT).

I. Payload Coverage

One of the most pleasant surprises about analyzing the Aireon hosted payload's coverage of ADS-B equipped aircraft is that the range of coverage far exceeds the design target. As discussed in early on orbit results [6, 7] the design goal for the minimum elevation angle of coverage from a single payload is 8.2 degrees (range of 2465 km) and the actual measured minimum elevation often extends to -4.6 degrees (3800 km).

Figure 1 shows a 60s time-lapse coverage plot of the payload on Satellite Vehicle (SV) 164 with a zero-degree elevation footprint outline at the current time (solid) and 60s in the future (dotted). The bottom half of the figure is a range histogram showing high position message counts at 3400 km with a trailing edge towards 3800 km. Considering the satellites move fast (~17,000 mph towards the poles) this histogram will change its characteristics quickly based on the location of the satellite and the ADS-B aircraft density and distribution.

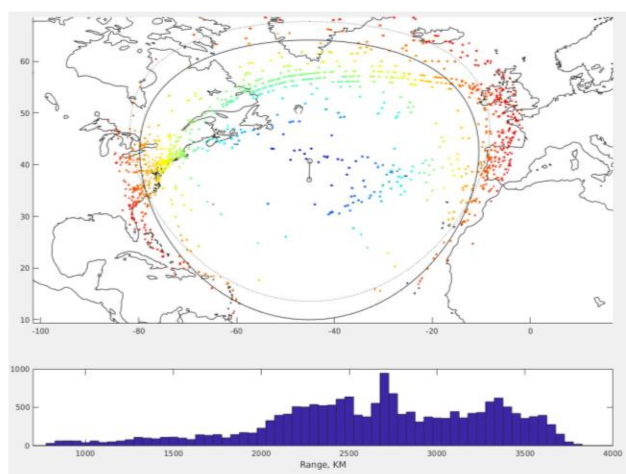

Figure 1: SV164 Coverage Plot and Range Histogram with a Zero Elevation Outline

Using an analog to the Minimum Trigger Level (MTL) of 90% of the nominal probability of detection (Pd), which is often used to define the edge of coverage for receivers, Aireon's MTL from an elevation perspective is measured to be approximately

0 degrees (3250 km). As will be discussed in the subsequent sections, the key TPMs of aircraft surveillance (Availability, Update Interval, and Latency) gain significant benefits from this extended payload footprint coverage.

II. Availability

Availability is the "promise" (and ideally realization) of meeting all the other TPMs. This can be calculated by:

$$A = \frac{MTBF}{MTBF + MTTR} \; or$$

$$A = \frac{Uptime}{Uptime + Downtime}$$

Where A = Service Availability, MTBF = Mean Time Between Failure, and MTTR = Mean Time to Repair/Restore. For any surveillance system, there is typically the concern about losing one of the receivers and how it may impact operations. Redundant systems are commonly put in place to reduce the likelihood of such incidents (e.g. collocating two receiver devices at each site) and therefore increase MTBF. Aireon has taken a similar approach with redundant receiver subsystems onboard each SV. Each SV also has 4 crosslinks and 2 feederlinks (which is somewhat analogous to having 6 telco links per asset).

If those redundant critical systems fail on a given SV/payload, then a coverage gap may exist. The size and timing of the gap depends on how well neighboring payloads can cover the area for a failed payload. Since the Iridium constellation converges at the North and South poles, overlapping coverage increases the closer a region is to the poles. Figure 2 shows how single (green), double (yellow), and triple or higher (blue) coverage looks for an assumed minimum elevation of 8.2 degrees for a snapshot in time. If this was the range of the payload, a single SV/payload outage scenario would cause about 8 minutes without coverage for an equatorial service volume 2-3 times per day until it's resolved. Above about 60 degrees of latitude (or below -60 in the southern hemisphere) there's always at least double coverage and therefore 1 SV outage would have no impact there.

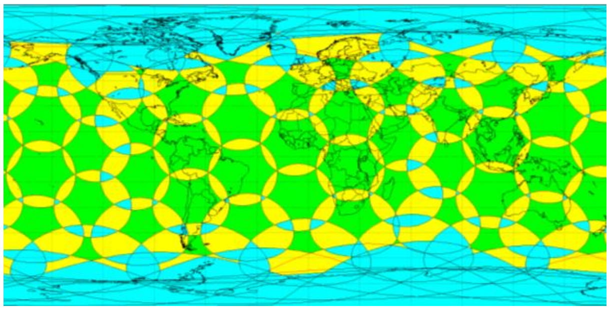

Figure 2: Coverage Overlap for Elev = 8 deg

However, if the minimum elevation coverage is closer to 0 degrees (as discussed in the previous section) then the areas of single-payload coverage shrink dramatically as shown in Figure 3. The latitudes of double or more coverage shift by 20 degrees to ±43 degrees. Additionally, the worst-case outage times for equatorial service volumes (such as Singapore FIR) reduce to ~3 minutes twice daily. Therefore, the MTBF (continuity of service) increased and MTTR decreased significantly, resulting in end-to-end service volume availability estimates above 0.9999.

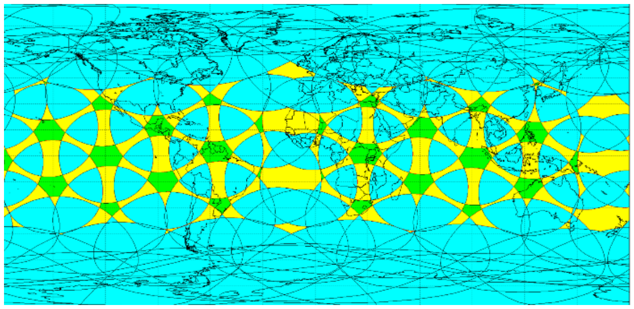

Figure 3: Coverage Overlap for Elev = 0 deg

Using a satellite dynamics simulation tool with Iridium's orbital configuration, test points were placed at latitudes of 0, 20, 30, 40, and 60 degrees. Over a range of minimum elevation angles (-5 to 8 degrees), the number of satellites covering each of these test points is calculated over a 24 hour period in 1 second time steps to determine the maximum duration that each of these points has single satellite coverage. The results from this simulation are summarized in Figure 4.

The observations of the results in Figure 4 indicate that the maximum coverage gap times decrease in nearly bilinear form for the latitude test points of 30 and 40 degrees with inflection points that have steeper slopes at 0 and 3.5 degrees, respectively. At the payload receiver MTL elevation of 0 degrees, latitudes above 40 degrees have no appreciable gap time, at 40 degrees it's just under 60 seconds, and for latitudes between 0-30 degrees the gap times are approximately 3.5 minutes. When there is a single payload outage, latitudes with gap times of 60 seconds or higher occur twice daily at the same longitude. For example, for a single payload outage, Singapore's airspace would experience a 3.5-minute outage in the first part of the day, then complete continuous coverage for 12 hours and then another 3.5-minute outage in the latter half of the day.

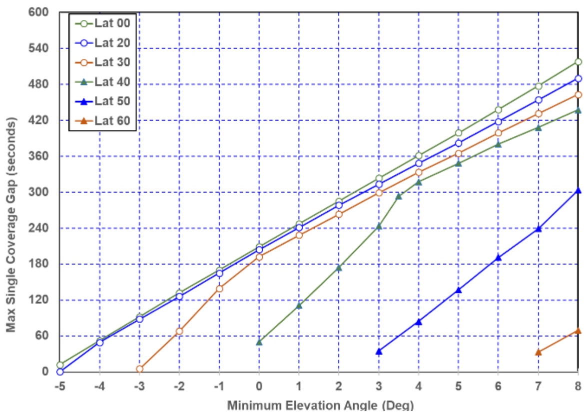

Figure 4: Maximum Single Coverage Gap vs. Elevation Angle in different Latitude Zones

Considering that most terrestrial surveillance systems have a MTTR of 30 minutes or greater, a worst-case "repair time" of 3.5 minutes is at least an order of magnitude better than the standard [8]. The anticipated outage behaviors related to the payload that would last greater than 24 hours have a MTBF of greater than 100,000 hours, which helps contain the overall risk such that a service volume availability of ≥ 0.9999 is achievable even for areas near the equator.

III. Latency

Latency is the delay measured from the time an ADS-B message is received at the hosted payload to the time an ADS-B report is delivered to the Service Delivery Point (SDP). The time of flight for a transmitted aircraft message to the reach the payload in space is less than 14 us and is rather insignificant when compared to the uncompensated latency of up to 400 ms within the ADS-B transponder. Since the ADS-B message is timestamped at the Aireon payload, uncompensated latency added to the transponder's budget is negligible, and the focus tends to be on the end-to-end latency (which can be compensated for by a tracker) within the Aireon system. The SDP is typically deployed at an ATC facility and locally networked to a tracker and automation subsystem.

The system latency budget required by ED-129B is 2.0s, which includes 1.5s to the edge of a distribution network and 0.5s within a distribution network to a tracker interface [8]. Aireon's design specification is for 1.5s (99%) to a SDP at an ATC site although a margin of about 200 ms is provisioned relative to this requirement. Figure 5 shows the results from a Monte-Carlo simulation estimating the expected system latency profile when aggregating the statistics from subsystem (e.g. payload, satellite segment, ground segment) latency requirements. Therefore, a design margin of approximately 700 ms is available relative to the ED-129B requirement.

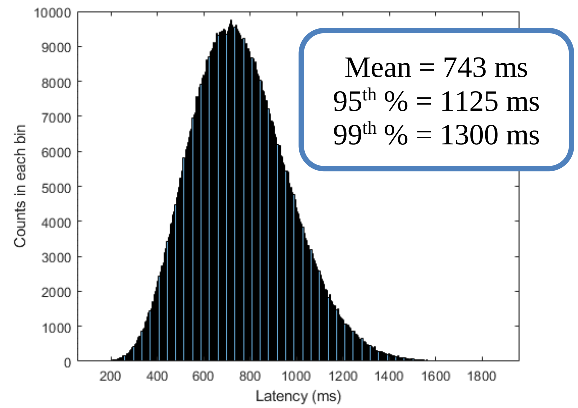

Figure 5: Requirements-based Model of Latency

As of Sept 2018, Aireon has 4 remote (at the customer location) SDPs deployed and 2 local (within the APD control station). Local SDPs should naturally have lower latency results than remote, but the observed results only show ~50 ms of difference between them. The measured results from the system can be visualized in Figure 6 with the aggregate statistics highlighted within the figure. These latency results, measured from the payload receiver to different end point locations, show an impressive 1655 ms of margin relative to the 2.0s requirement. Latency characteristics of 345 ms (99%) are clearly well within the same domain as terrestrial surveillance systems and in some cases faster.

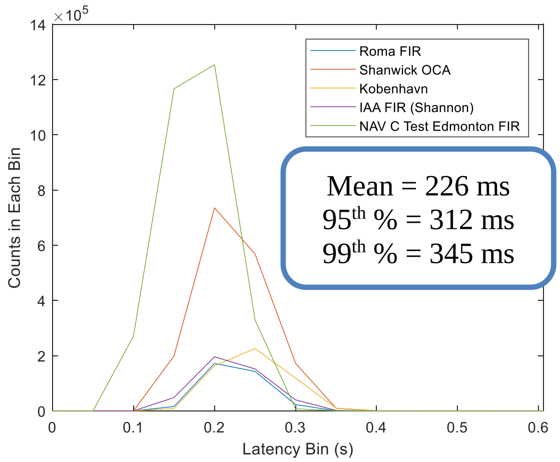

Figure 6: Measured Latency to 5 SDPs

There are slight dependencies of latency on geography wherein the more northern latitudes will tend to have lower latencies as shown in Figure 7 due to their closer proximity to a teleport site (such as Svalbard, Norway), but these variations are less than 50 ms at the 95th percentile.

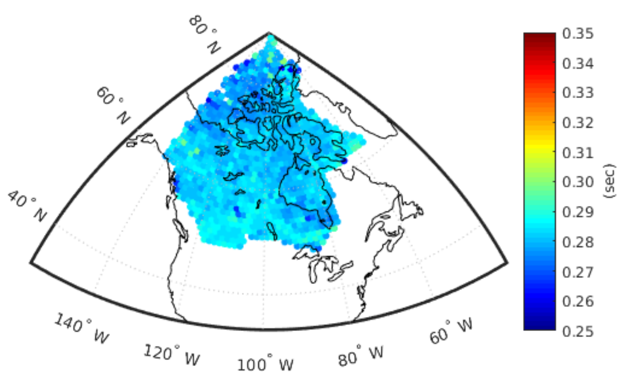

Figure 7: Edmonton FIR 95th % Latency Grid

IV. Update Interval

The update interval (UI), or more appropriately the probability of update (P_{UI}), is measured at the SDP from a population of time intervals between sequential ADS-B reports for each respective aircraft. For low density en-route (5 NM separation) airspaces, the requirement from ED-129B is to meet a UI of 8s with a probability of 96% or higher. To achieve this level of performance, the mean aggregate Pd of the receivers needs to be greater than or equal to 18.2% [9].

Consistently achieving that degree of performance can be challenging when taking into consideration aircraft transmit power, additional attenuation to the bottom antenna, high interference environments, and limited bandwidth and power resources on the payload [9, 5, 7, 10]. However, since solutions to these challenges were developed early in the Aireon program along with the flexibility to adapt and tune post-launch, the results in this section will demonstrate the achievements made thus far to address these challenges.

One mitigation to the temporary limitations in bandwidth (which will be resolved by routing changes in Nov 2018) was to reduce the number of payloads providing service to 55 (only 5 out of 6 orbital planes) and allocate all available bandwidth to this "mini-constellation". With only 55 payloads in use, the UI was measured over the Reykjavik FIR showing near uniform results throughout the airspace at a P_{UI} of approximately 99% for an 8s UI (see Figure 8). Figure 9 shows the full histogram of UI results as an aggregate over the 3-hour window the service volume had full coverage.

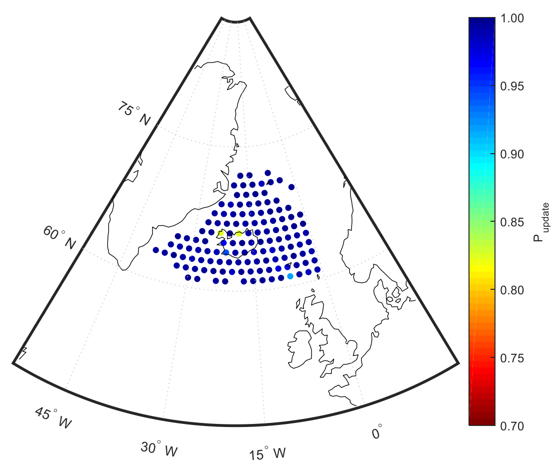

Figure 8: Reykjavik FIR P_{UI} Grid

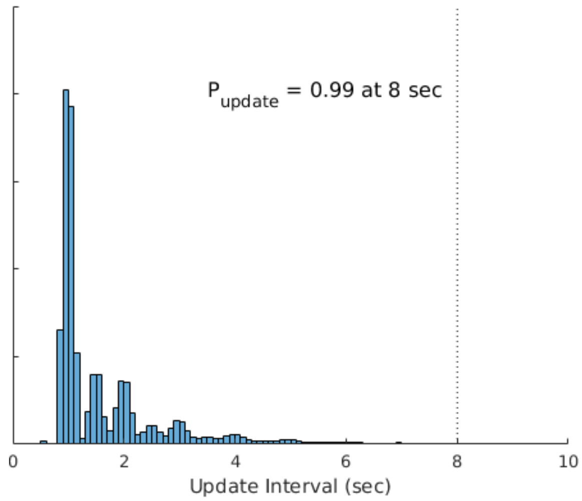

Figure 9: Reykjavik FIR UI Histogram

Update interval can also be viewed within various segments of the population to determine how they perform relative to the majority population or intended use. As an example, several aircraft types, such as the Cessna 402C, typically have bottom-only antenna transponders. In prior work, the relative attenuation from the top to bottom antenna over the elevation angle was estimated to be linear [9]. This means that reception of messages from a space-based ADS-B receiver to an aircraft's bottom antenna would be best at lower elevation angles (nominally below 20 degrees). However, given the extended range described in Section I, elevation coverage below 8 degrees offers additional detection opportunities that can lead to beneficial performance. Figure 10 shows a track from a bottom-only ADS-B aircraft flying from Puerto Rico SJU airport (latitude ~ 18.4º) to St. Thomas. Although there are a few gaps in coverage, the P_{UI} over 30s intervals is 98.5%, which could be suitable for situational awareness and tracking applications. Additionally, this performance is expected to further improve with the additional 11 payloads of coverage and increased bandwidth. Performance is also expected to improve at latitudes closer to the poles due to the increase in low elevation angle coverage opportunities. By comparison, smaller satellites (e.g. cubesats, nanosats) would likely have more difficulty detecting bottom-only aircraft since their smaller aperture receivers would have more channel fading at lower elevation angles.

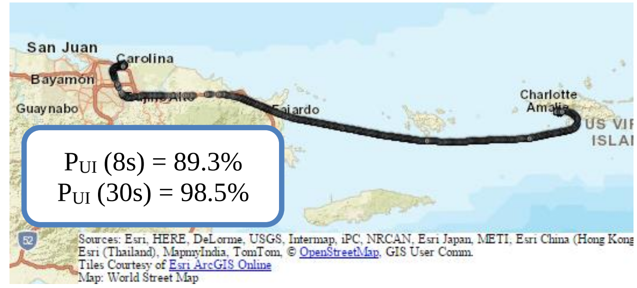

Figure 10: Cessna 402C Bottom-Only Reception from Puerto Rico to St. Thomas

Another example segment of the ADS-B aircraft population is that of aircraft that are on the surface of an airport. The airport surface can be a busy environment and there are often challenges for terrestrial systems with finding suitable sites to provide adequate coverage of the entire movement and non-movement areas. Considering the Aireon payload has an extreme bird's eye view at 780 km, building shadowing and link margin differences relative to 18,000' (5.5 km) are typically insignificant factors from space. Additionally, upon landing, most aircraft with diversity antennas will broadcast all messages out of their top antenna which is beneficial for a space-based receiver. Figure 11 shows an example of a coverage plot at Keflavik (KEF) airport in Iceland over a 24 hour period. The aggregate P_{UI} (5s and 8s) is 99%, which is aligned with the results from the whole FIR shown in Figure 8 and Figure 9. The combined performance would provide a seamless continuity of service from en-route (8s) to terminal/approach (5s) to surface (although surface would require a UI of 1s).

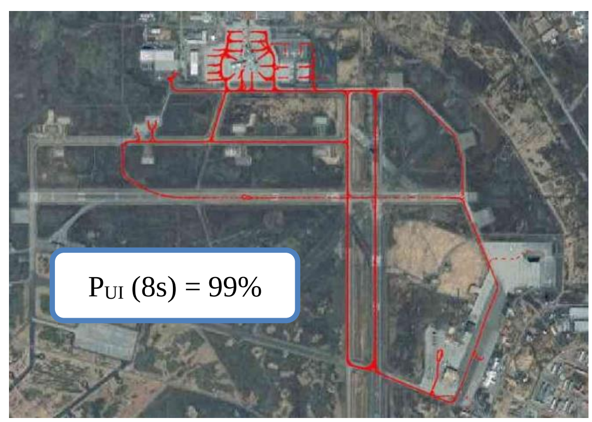

Figure 11: Surface coverage of Keflavik Airport

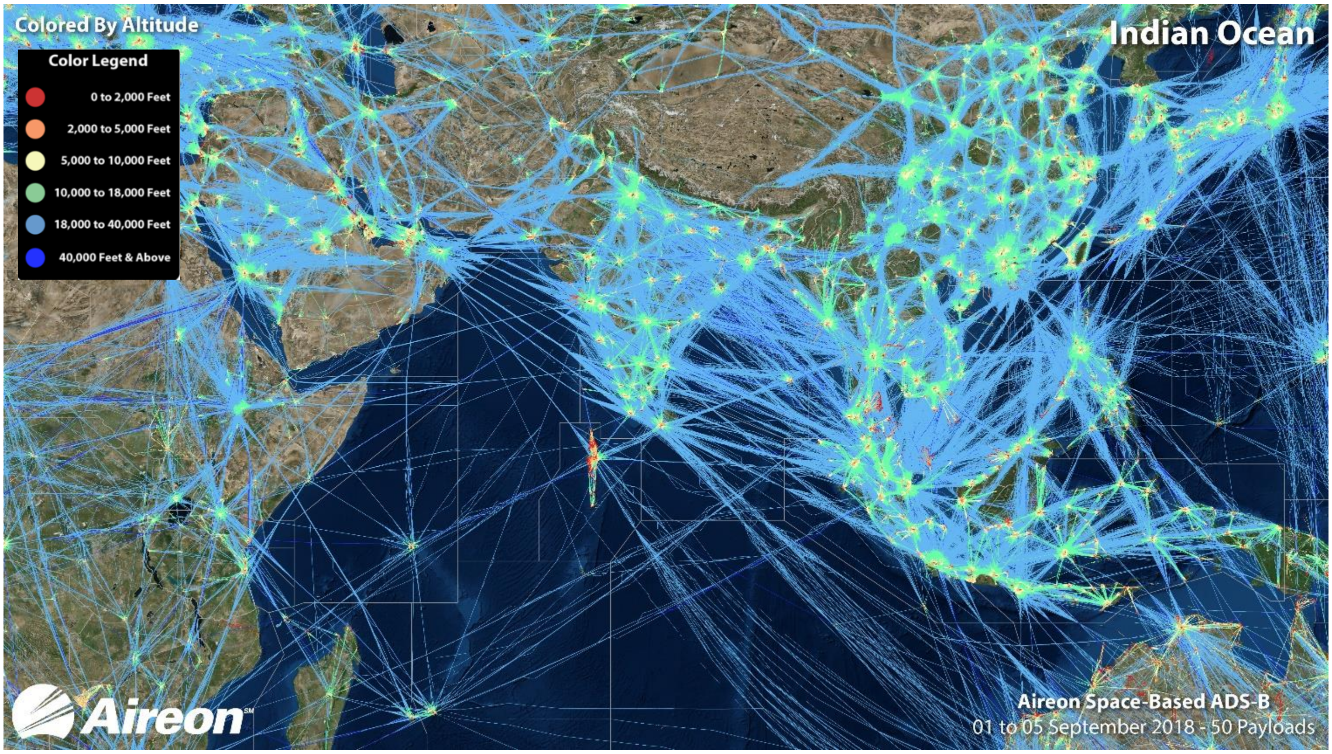

Figure 12: Aireon's ADS-B Coverage (Colored by Altitude) from Sept 1-5, 2018 with 50 Payloads

V. Conclusion

The key surveillance TPMs of availability, latency, and update interval were demonstrated in this paper from the Aireon system. In each case, significant margin was found in the measurements relative to the internal and external requirements. These results were achieved even with a partial constellation and other temporary constraints. Even in this state, Aireon receives about 10 billion ADS-B position messages per month and this number is expected to rise by several fold by the end of 2018. Figure 12 shows a depiction of the coverage over several areas in the southeast region of the world with altitude color contrast highlighting areas with terminal, airport, and helicopter operations. Clearly the potential of this system has only begun to be explored, giving rise to new metrics and applications in the ADS-B frontier.

VI. Acknowledgements

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