# Long-term testing of acoustic system for tracking low-flying aircraft


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***Abstract*— Stevens Institute of Technology conducted a long-term test of an acoustic system designed to track low-flying small aircraft in remote locations. The system consists of 4 nodes located between 1 and 4 km apart in a mountainous terrain. Each node is comprised of a pyramid-shaped volumetric cluster of 5 microphones, an embedded computer, and a pan-tilt-zoom camera steered to detected targets in real time. A communication device was used to transfer data to a centralized location. Each node estimates the direction of arrival toward the sound sources and sends it along to a central processing computer. The central computer combines the data from all nodes to generate tracks and classify targets. The duration and the scale of the deployment allowed to identify and solve many problems, including the effects of propagation delays between nodes on cooperative localization and tracking, the seasonal changes in environmental noise, persistent and transient noise sources, and the diversity of targets of opportunity and their signatures. The propagation delay effects led to the development of separate trackers for review of target trajectories and for immediate action such as automatically steering the camera.**



***Keywords—signal processing, passive acoustics, low-flying aircraft***


## I. Introduction

Detection of an aircraft by a passive acoustic system based on the noise emitted by the target itself was first used in World War I, and was superseded by radar technology over time.

However, the radar's performance is limited when used to track low-flying aircraft in some terrains, in particular executing a low-altitude "nap-of-the-earth" flight course within a terrain that blocks direct line-of-sight from monostatic radar and reducing the performance of optical detection and classification against the complex background. Due to comparatively low cost, passive acoustic systems provide a promising alternative to radar detection and are able to detect aircraft flying low by employing sensors placed in the area of observation.

Stevens Institute of Technology developed algorithms for the detection of low-flying aircraft using passive acoustics to provide a warning of the aircraft's presence.

Stevens Institute of Technology developed the Acoustic Aircraft Detection system (AAD), a passive acoustic wide area surveillance system. A Long-duration test of the passive acoustic system for tracking low-flying aircraft begun in September 2013 [1][2]. In the second phase, the system was updated based on this experience and further testing was conducted.

Differing from other passive acoustic systems [3], the physical design of the field stations was explicitly targeted for long-term deployment, with provision for potential snow cover, an autonomous power source provided by a renewable power source, and human-portability of all components required to assemble a node, with weight under 80 pounds. The algorithms were updated to improve the tracking [2] and classification [4] of an aircraft based on acoustic signature, utilization of various criteria for rejection of false alarms, camera cueing and providing the system with resiliency in case of failures of one or more nodes.

Compared to several other distributed passive acoustic systems found in the literature [5]–[8], the AAD featured a wider frequency band (50 Hz to 4 kHz), which permitted improved classification of targets by acoustic signature [4].

## II. Description of Acoustic Nodes

The system consists of several AAD nodes (shown in Fig. 1a) also referred to as field stations (FS), each is equipped with a volumetric cluster of five microphones that are connected to an electronics box, where the signals are digitized and preprocessed by an embedded computer.


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The field station consists of a mast (3 in Fig.1) in the center that elevates a frame (5 in Fig.1a). The frame holds an array of five microphones (1.1-1.5 in Fig.1a) in a pyramid configuration. Three microphones (mic.1-mic.3) are in an equilateral triangle parallel to the ground inscribed in the circle with a radius of 122 cm at the bottom, one is in the center (mic. 4), and one (mic.5) is 227 cm directly above the central microphone.

The mast (3 in Fig.1a) is telescoping with 4 sections 165 cm collapsed, extended by pumping air inside using the built-in pump, to a length of 498 cm. Finally, the metal struts were added for support (4 in Fig.1a), giving the structure stability without guy-wires.

The electronic box (2 in Fig.1a) contains an embedded computer that is connected to the data acquisition along with other electronics that control the power distribution. Data acquisition is based on National Instruments cDAQ-9184 with two NI-9234 modules connected to the microphones that are capable of 24- bit dynamic range and for which the scale of ±5 volt peak sampling, during the test was set to 12.8 kS/s allowing the bandwidth of 6.4 kHz to be analyzed. A Garmin 19x GPS receiver (6 in Fig.1a) is placed at the top of the mast and is connected to the electronics box to provide time synchronization and self-localization. A speaker (7 in Fig.1a) at the top of the mast is used to conduct experiments remotely, such as measuring the speed of sound.

An inexpensive visible light Pan-Tilt-Zoom (PTZ) camera (see 8 in Fig. 1a) was employed to acquire images of the targets from multiple angles.

The radio communication device (6 in Fig.1a) permits sending and receiving data to and from the central processing computer. Different commercial license-free wireless radios were used for this purpose throughout the testing period including 5.8 GHz, 2.4 GHz and 900 MHz radios, and it has been observed that they could all reliably cover a bandwidth of about 1-3 Mbits/second over the distance of up to 20 km. The 900 MHz Ubiquiti NanoBridge M9 was able to communicate even in conditions of obstruction in the Fresnel zone.

The power provided by a renewable power source (see Fig. 1c) was provided by NREL. Initially, the power source was based on flexible solar panels, during the second phase higher efficiency rigid solar panels were installed, where the batteries, the fuel cell and controller electronics were integrated into a single enclosure.

## III. Deployment description

During the testing, four field stations were deployed in an area with a rugged mountainous terrain at different sites separated by 1.2-4.2 km. The placement of the stations along with the predicted probability of detection of a target flying at a fixed altitude of 1000 m relative to mean sea level (MSL), or 100-400 m above ground level (AGL) is shown in Fig. 2, based on a digital elevation model (DEM), station direction probability and precision, and geometric factors - as previously reported [9][10].

The data is sent to a Central Processing Station (CPS), deployed at a separate location about 20 km away, that aggregates data from all the stations and produces the tracks.

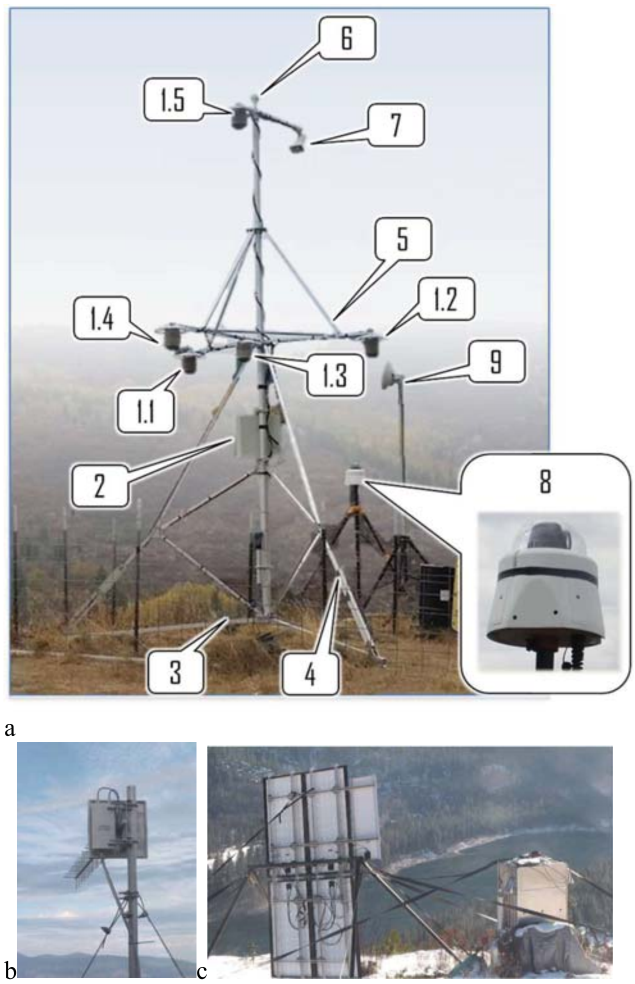


Fig. 1. Acoustic site, a - acoustic field station with the elements annotated, b – 900 MHz ISM band communication device, c – renewable power source provided by NREL

### A. Calibration procedure

An acoustic calibration procedure was introduced to reference the orientation of the station to true North. It requires an inexpensive horn megaphone placed 50-100 m away from the station with a GPS receiver; a white noise signal is emitted over a period of time. While the white noise produces a very strong response in the direction finding and produces a very precise direction estimate, it is not as disruptive as other types of signals (sirens or tones). Averaging GPS measurements for the receiver in the station and near the horn improves the position estimate to less than a meter, thus allowing to compute the true course between the various locations and compute the rotation necessary for correct direction finding.

## IV. Tracking the targets

Tracking is performed using two separate subsystems: a near-real-time and a post-processing trackers. The real-time tracks are used for immediate response, such as steering the camera, while the post-processed tracks are used for review of activity and those include filtering by the minimum duration of

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the track. The post-processing tracks are made available as soon as the transit is finalized and sufficient context is available.

Controlled flights with aircraft carrying GPS receivers were conducted involving different types of aircraft: small airplanes, small helicopters, a gyrocopter, and an ultralight aircraft. A particularly new target considered was the gyroplane, a lightweight aircraft. An example of the track is shown in Fig. 2, while Fig. 3 shows the images of the aircraft during the flyby along with the spectrogram.

Additionally, over 3000 flights of targets of opportunity were observed, with their signatures recorded. The observed flights included aircraft similar to the ones used in contrived tests as well as larger turboprop planes, and large jet high-flying aircraft with altitudes up to 10 km. The targets of opportunity frequently flew at low altitudes of 100-200 m AGL and the shape of the terrain influenced the AGL altitude and flight paths.

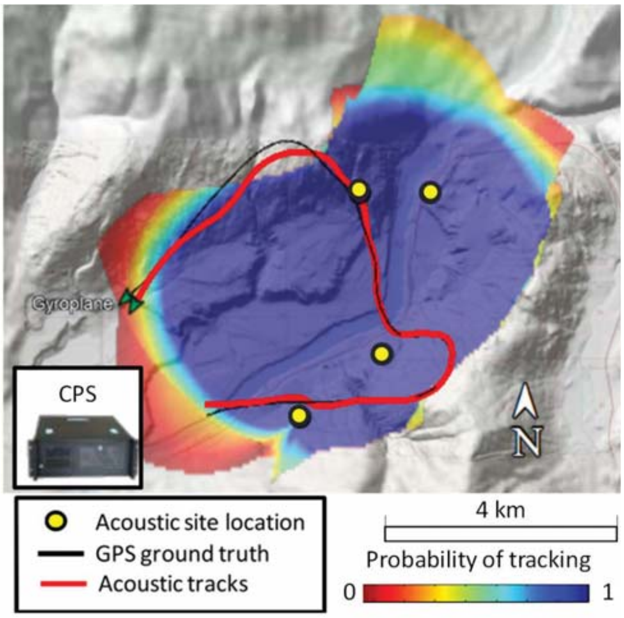


Fig. 4. . Elements of the system in the deployment area (four nodes and Central Processing Station), predicted tracking probability distribution (67 sq km. covered) and the acoustic track of the aircraft.

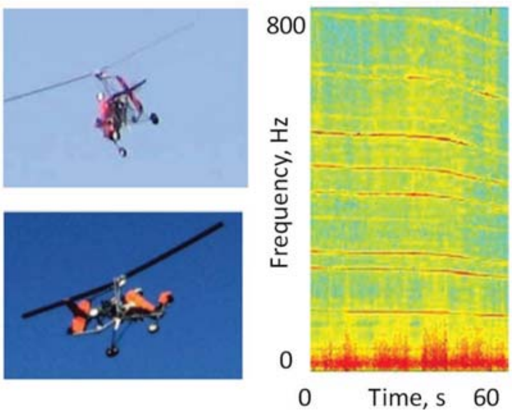


Fig. 5. . Images of and spectrogram of the autogyro during a flyby

The maneuvers were undertaken typically to follow the terrain features at low altitude.

Fig. 4 and 5 respectively show the tracks, pictures and spectrograms of acoustic signatures of select targets of opportunity. Figs.4a, 6a show a typical target – a small plane. A notable part of the targets of opportunity was a large commercial jet aircraft as seen in Figs. 4b and 5b. In an unusual occurrence, the system has captured the acoustic signature of a biplane as shown in Figs. 4c and 5c.

During the deployment, the information from the acoustic system was provided to a command center, along with other systems participating in the experiment. The AAD provided the tracks supplemented with spectrograms, audible sounds, and video and classification results.

### *A. Classification of tracks*

The classification of targets forming tracks is performed at the central processing station, based on the previously reported methods [4] and is applied to post-processing tracks and

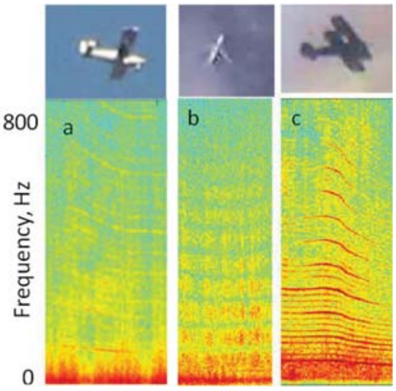


Fig. 2. Examples of targets and their spectrograms: a – small plane (classified as "with propeller/small plane"), b – a biplane (misclassified as "helicopter"), c – large jet aircraft (classified as "jet high above") transiting 7 km above ground

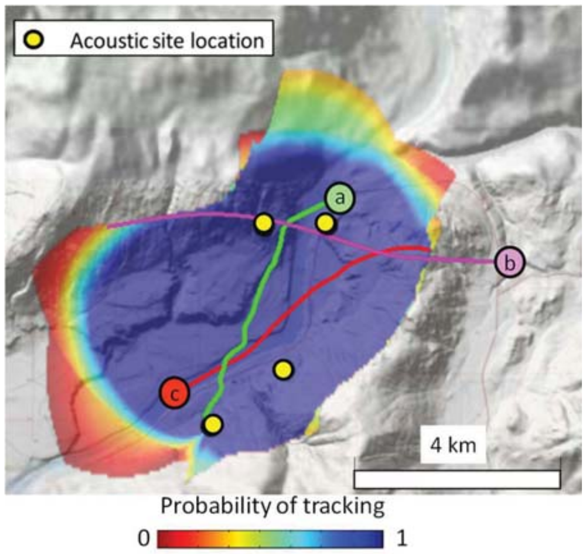


Fig. 3. Tracks of target of opportunity (captured on different days): a – small plane b – a biplane, c – large jet aircraft. Color scale shows predicted

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associated compressed acoustic time series data sent by the stations to the CPS. By estimating the distance and closest point of approach, we were able to achieve extraction of the sound samples best representative of a particular target.

The initial classification is performed for broad classes: "with a propeller," "ground object," "jet high above," or "unknown." The class "with propeller" can be further classified as "plane," "helicopter," or "ultralight aircraft."

Each layer of classification has a confidence measure associated with the result. The layered classification permits to include the possibility of some noise sources forming tracks.

A biplane target of opportunity was not one of the expected classes of signature and was misclassified as a "helicopter" based on the known features associated with helicopters. This along with other examples shows that the classification in a real environment is an open-ended task as the types of targets exist beyond any fixed target matrix.

## V. Prediction of Coverage and Precision

The methods reported previously [10][2] for the acoustic system performance prediction were validated by the data during numerous controlled tests.

These methods permit finding the probability of tracking (as shown in Fig. 5 as the colored overlay). The precision of localization was also estimated (see Fig. 7a) and validated by measuring and averaging the actual root-mean-square error relative to GPS (see Fig. 7b).

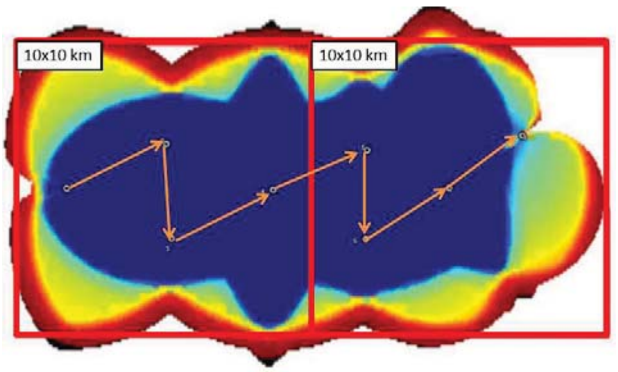


Fig. 6. Deployment plan for gradual extension of coverage, each additional site adds 25 sq.km. coverage (colors the same as in Fig. 5).

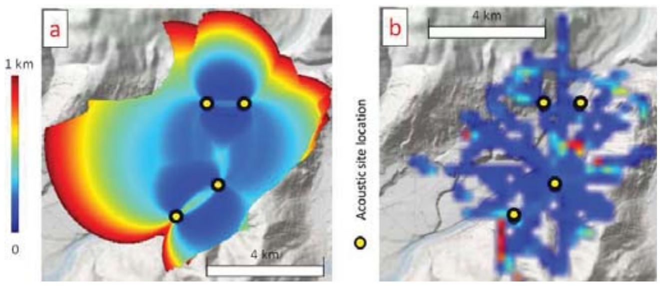


Fig. 7. Experimental verification of accuracy, a - predicted standard horizontal position error for target at 1100 m MSL (0-600 AGL), b - root-mean-square error of tracks of helicopter. The color scale is the same for both a and b

### A. Scalability of the system

The required number of field stations needed to cover a particular area can be estimated using coverage prediction methods. A schema assuming a flat terrain and deployment of sites in a zig-zag pattern and corresponding coverage is shown in Fig. 8. At least three sites are recommended for a minimum configuration; then the coverage is extended with the addition of each new site.

On average, one site increases the coverage by 25 sq. km on a flat terrain. On hilly or mountainous terrains, the coverage ranges between 12-25 sq. km per site due to terrain obstruction of line-of-sight. The performance prediction methods are intended to help choose the concrete site locations before deployment to cover the desired area.

The limitation on the number of nodes per central processing station is imposed primarily by communication bandwidth. It is possible to extend the network indefinitely by segmenting the network into separate groups of nodes, served by separate central processing stations, while the data products from each CPS would be unified by a fusion tracker, treating the tracks as measurements. An example of a fusion tracker to integrate heterogeneous systems was presented in [11].

## VI. Noise Rejection

Rejection of noise is a significant challenge even in remote areas, as the sources of noise may be both man-made and natural. Even in remote areas, there is an infrastructure that facilitates human activity such as roads, railroad, and various machinery. Natural sounds are produced by wildlife and the interaction of wind with trees[3].

Initially, the system required manual choosing for the exclusion of directions with frequent noise and use of a manually selected elevation angle mask (e.g., reject anything 3 degrees below the horizon). The sources that were found below a specific elevation were rejected at the direction finding stage.

The majority of noise sources affecting the system were stationary, and the directions toward them could be enumerated by prolonged observation. During the second phase of testing, an automated algorithm was developed for noise rejection that learned the directions to the persistent source and created small and adaptive notches without user intervention.

An example of a persistent source of noise is shown in Fig. 9. The source of noise is the breaking water on a river depicted in (Fig. 9a). The 2D histogram of frequency of detection over azimuth and elevation angles accumulated over 30 minutes (Fig. 9b) shows a distinct peak for the direction towards the white water. Aircraft are moving and unlikely to stay at one direction (from the perspective of the node) for more than seconds, contrasting them from persistent noise sources. The generated notches were so small, that they did not appreciably affect the detection of an aircraft.

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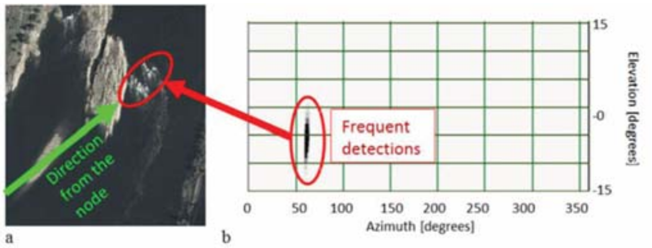


Fig. 8. Directional statistics of noise, a - map of the location (image from USDA FSA) and direction identified, b - histogram of direction finding over 30 minutes (black- frequent detection in this direction, white – no detection ).

The post-processing tracking subsystem was helpful for rejecting tracks that were too short (15 seconds or shorter) for review purposes. Aircraft were consistently detected for longer periods, than the tracks resulting from any intermittent sources.

The classification was helpful as well, by permitting the "ground object" classification to be assigned to targets of no interest, thus eliminating the ground targets making it through the initial layers of track filtering from the review.

## VII. Camera steering

The camera steering is an inherently real-time activity. However, the speed of sound (330-350 meters/second) may introduce significant delay, for example even for a target at 1.5 km the delay will be about 4.5 seconds, enough for the target to move significantly. The propagation delay forces us to extrapolate the track into the future to acquire the current position of the target and point the camera. In the case of a maneuvering target, this extrapolation creates the potential for error in steering. This problem is not present in post-processing tracks, as we do not have to extrapolate.

While the images were acquired in real-time on a best-effort basis, the videos associated with the tracks could be produced only out of images that contained the target, according to post-processed tracks and the images can be cropped to better center it on the targets, within the frame. For example, see Fig. 11a: the image with 12 degreed horizontal field of view of a target 1.2 km away is captured by pointing to real-time track. The target just slowed down to drop off a load suspended by a cable (see Fig. 11b), as a result of the change in speed, the estimated direction for the camera (center is shown as a red dot) overshoots the current location and is further right than the target. The post-processing track permits cropping a smaller 5 degree-wide 800x600 subimage (red rectangle in Fig. 11a) out of the original 1920x1080. The central part of the subimage is shown in Fig. 11b, showing the target centered in the view. The subimage is small, increasing transmission speed over limited bandwidth and provides more precise centering of the target.

The acoustic steering of the camera can find images of the target that would not be easily distinguishable to a computer vision algorithm, but will be useful to the user.

## VIII. Operation history

During the initial period of 282 days, the system was available 97.5%, with minor outages caused by problems with network service, and autonomous power source outages. Throughout the installation, only a few outages were caused by software problems, amounting to 2 days. One outage was due to one of the stations stopping to send data and CPS pausing the processing until the data from all stations was received. This prompted the addition of the detection of inactive stations, thus making the system resilient, so that failure of stations only reduces coverage, but does not cause a complete outage. No failures of the sensor electronics that are part of the field stations were observed.

During one summer, the CPS being placed in a non-air-conditioned location failed, the processing was immediately transferred to a spare. Future installations were performed in appropriately climate-controlled environment.

Microphones returned from the field after 3 years were tested outdoors by emitting a chirp sound with a frequency between 100 Hz and 10 kHz from the speaker placed at a distance of 2 m and comparing the output of several microphones to a calibrated measurement microphone. They were found to have the same sensitivity as the newly manufactured microphones within 6 dB.

a

b

Fig. 9. Improvement of captured image of the target 1.2 km away by using post-processing tracks. a) full field-of-view image (horizontal field of view = 12 degrees) captured using the real-time track for steering, b) cropped cetral part of the subimage showing details.

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## IX. Conclusion

A system for low-flying aircraft detection was tested for an extended period, demonstrating localization and tracking of the targets and operation through seasonal changes and survivability.

The custom design of the microphones employed in the acoustic stations was proven to survive for the entire duration of the deployment without appreciable degradation. Data from the system's performance during various operating conditions were recorded.

The classifier performed sufficiently well to provide additional useful information. However, the variety of the targets occasionally lead to misclassification requiring constant expansion of classification capability.

The rejection of false alarms was improved based on experience and was automated. The directional and duration statistics were successfully used to reject stationary sources and the intermittent strong sources of noise. The area of deployment was remote, but still included many sources of sound including roads that were active throughout the day.

The results helped establish the performance baseline of the system and allowed us to create a model to predict it in future deployments based on the freely available data, such as digital elevation models and maps of local roads. Plans for scalability of the surveillance system to any size have been analyzed to estimate the number of stations and central processing computers to achieve coverage of any given area.

The system can be applied for providing surveillance coverage in remote mountainous areas, where monostatic radar detection may be difficult to achieve due to line-of-sight limitations. Multiple unattended sensor nodes operating on renewable energy and communicating using long-range radios may be positioned to best close gaps in coverage. The modeling permits prediction of coverage before physical deployment to estimate the number of nodes required.

## Acknowledgment

This project was funded under contract with the U.S Department of Homeland Security (DHS) Science and Technology Directorate (S&T). The opinions contained herein are those of the contractors and do not necessarily reflect those of DHS S&T.

Dr. Alexander Yakubovskiy is acknowledged for developing the classification subsystem.

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