



# Exploring Spatial Patterns of Overflights at Mount Rushmore National Memorial, Updated 2023–2024



Mount Rushmore National Memorial.  
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# Exploring Spatial Patterns of Overflights at Mount Rushmore National Memorial, Updated 2023–2024

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Davyd H. Betchkal <sup>1</sup>, Tyra A. Olstad <sup>1</sup>, Brian A. Peterson <sup>2</sup>, J. M. Shawn Hutchinson <sup>2</sup>,  
J. Adam Beeco <sup>1</sup>

<sup>1</sup> National Park Service  
Natural Resource Stewardship and Science  
Natural Sounds and Night Skies Division  
Fort Collins, Colorado

<sup>2</sup> Kansas State University  
Manhattan, Kansas

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## Abstract

The purpose of this analysis is to monitor changes in the spatial patterns of overflights at Mount Rushmore National Memorial (MORU) after the implementation of the park's Air Tour Management Plan (ATMP). Overflights were compared across 2023 and 2024 using Automatic Dependent Surveillance–Broadcast (ADS-B) data collected over identical timeframes, May 15<sup>th</sup> to June 25<sup>th</sup>. This report expands upon an initial 2022 study that revealed a ring-like spatial pattern of overflights near MORU below 1600 feet mean sea level (MSL; Peterson et al., 2022). Data processing followed standardized protocols using the NPS ADS-B Toolbox (Hutchinson and Peterson, 2024), consistent with other recent analyses (Peterson et al., 2024a; Peterson et al., 2024b; Olstad et al., 2024; Gurung et al., 2024; Peterson et al., 2025; Olstad et al., 2025; Gurung et al., 2025). New effectiveness monitoring methods (Reynolds et al., 2016) were applied within a 330 km<sup>2</sup> rectangular study area encompassing the local air transportation network. Waypoint- and raster-based techniques were used to detect changes in overflight density and distance from boundaries. Results indicate a substantial reconfiguration of overflight patterns consistent with ATMP implementation. The ATMP is estimated to have produced a sound level benefit of  $\Delta L_{eq,1s[12.5-20,000\text{ Hz}]} = -2.8\text{ dB}$ , equivalent to a 50% reduction in acoustic energy exposure and an equivalent doubling of acoustic active space during noise events. These findings suggest that the new, self-organized overflight patterns around MORU achieved an operational fit that improves the acoustic environment and protects park resources and values. This outcome demonstrates that airspace adaptations to minimize noise impacts are not only feasible but can yield durable spatial configurations that meaningfully balance access and resource protection.

## List of Terms or Acronyms

**Active Space:** The three-dimensional space within which a specific sound source remains audible to a listener, depending on the source's loudness, the sound-carrying properties of the environment, and the background sound where the listener is.

**AGL:** Above ground level

**ADS-B:** Automatic Dependent Surveillance–Broadcast

**ATMP:** Air Tour Management Plan

**DEM:** Digital Elevation Model

**Effectiveness monitoring:** Monitoring to document system response to a management action, noting the degree to which the desired outcome was attained. Used when timing of an action is planned and there is relatively low uncertainty regarding the expected response.

**FAA:** Federal Aviation Administration

**GIS:** Geographic information systems

**MORU:** Mount Rushmore National Memorial

**MSL:** Mean sea level

**NPS:** National Park Service

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# Introduction

The purpose of this analysis is to monitor changes in the spatial patterns of overflights at Mount Rushmore National Memorial (MORU), after the implementation of the park's Air Tour Management Plan (ATMP). Overflights were compared across 2023 and 2024 using Automatic Dependent Surveillance–Broadcast (ADS-B) data collected over identical timeframes, May 15<sup>th</sup> to June 25<sup>th</sup>. This report extends upon an initial study which revealed a ring-like spatial pattern of overflights over MORU below 1600 feet mean sea level (MSL; Peterson et al., 2022). In the present study, the scope of analysis is a 330 km<sup>2</sup> rectangular study area which bounds the salient features of the previously revealed patterns (Figure 1).

MORU is located in southwestern South Dakota, two miles southwest of Keystone, along State Highway 244, and is comprised of 1,278 acres. Mount Rushmore preserves a diverse cultural and natural landscape, including a traditional cultural landscape of great importance to Northern Plains Tribes. It is an internationally recognized symbol of freedom and democracy which showcases a unique engineering and artistic achievement with significant sociocultural ramifications. The majority of visitation is to see Mount Rushmore's iconic Shrine of Democracy sculpture and associated visitor facilities. Both the Grand View Terrace and the Ranger's Amphitheater (43.87730° N, -103.45642° W) are popular locations to view the sculpture. The sculpture is also popular to view by air tour.

The data collection, cleaning and reduction methods of this study use the NPS ADS-B Toolbox (Hutchinson and Peterson 2024) and are identical to several other recent reports (Peterson et al., 2024a; Peterson et al., 2024b; Olstad et al., 2024; Gurung et al., 2024; Peterson et al., 2025; Olstad et al., 2025; Gurung et al., 2025). We extend these analyses with new effectiveness monitoring (Reynolds et al., 2016) methods to reveal changes after the establishment of the MORU Air Tour Management Plan (ATMP).

From 2019–2023, commercial air tour operators reported an annual average of 4,778 air tours conducted at Mount Rushmore (Ahern et al., 2025). The National Parks Air Tour Management Act of 2000 (NPATMA) (Public law 106-81) requires the National Park Service (NPS) to work with the Federal Aviation Administration (FAA) to manage air tours at all units that receive more than 50 air tours per year, with the exception of Grand Canyon National Park and all national parks in the State of Alaska (Beeco and Joyce, 2019). The MORU ATMP was signed on November 15, 2023, with an effective date of May 13, 2024. The ATMP prohibits air tours within ½-mile of the MORU park boundary and within 5,000 feet above ground level (AGL) of this area. Adherence to the ATMP would require different air tour travel patterns than those that existed prior to May 13, 2024, and described in Peterson et al. (2022).

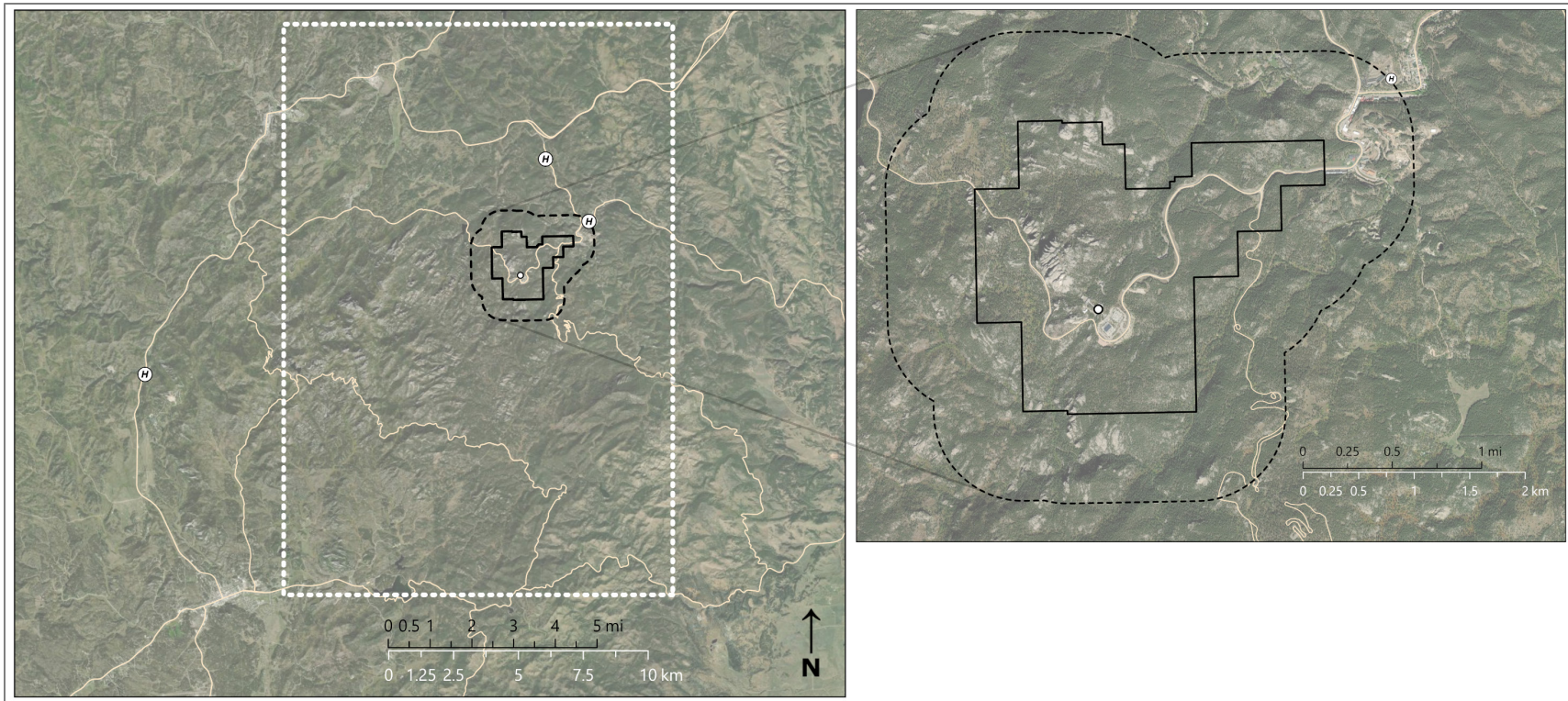


**Figure 1.** The geographic features relevant to MORU overflight monitoring. Shown are the MORU boundary (solid black line), the ATMP boundary (dashed black), the study area (dotted white), local roadways (khaki), local helipads (“H”) and the ADS-B data logger location (small white dot within MORU boundary). On the right, a secondary 1:23,000 scale map details the position of the ADS-B logger, with the Ranger’s Amphitheater to the northwest.

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# Methods

## Data Collection

Data were collected by an ADS-B data logger positioned with an unimpeded and expansive skyward exposure atop the Gift Shop and Café building owned by the NPS Concessionaire Xanterra (43.87650° N, -103.45495° W; Figure 1). The same logger was used during both periods of observation, with exactly the same position and orientation. The logger recorded ADS-B signals as text files.

As of January 1, 2020, the Federal Aviation Administration (FAA) requires all aircraft that enter designated airspace to be equipped with Automatic Dependent Surveillance–Broadcast (ADS-B) technology (see 14 CFR § 91.225 and 14 CFR § 91.227) (FAA, 2023a). ADS-B signals are transmitted from aircraft and provide location information and unique identifiers to improve airspace safety and air traffic efficiency (FAA, 2023b). However, the airspace over MORU does not require ADS-B. Regardless of the airspace designation, prior studies suggest a rather ubiquitous adoption of ADS-B by aircraft in the United States (Peterson et al., 2022; Peterson et al., 2023).

## Data Processing and Cleaning

Data processing, cleaning, and analysis were accomplished using a custom ArcGIS Pro toolbox with six Python-based geoprocessing tools that automate and simplify the analysis of ADS-B data (Hutchinson and Peterson 2024). The toolbox conducted the following tasks: processed raw ADS-B data files (Tool #1), created waypoint and flightline feature classes (spatial reference = North American Datum 1983 Universal Transverse Mercator Zone 13N) (Tool #2), merged daily waypoints and flightlines (Tool #3), and screened for flights known not to be air tours (Tool #4). Previous studies to explore the spatial patterns of overflights also use Tools #5 and #6, but they were not required for the effectiveness monitoring purposes of this study.

This report expresses altitude in terms of both mean sea level (MSL)—the altitude of an aircraft above sea level, regardless of the terrain below it—and AGL, which measures the distance between the ground surface and the aircraft. To calculate AGL altitudes for each waypoint, a 1/3 arc second 10-meter digital elevation model (DEM) was used (United States Geological Survey, 2024). The AGL altitudes were calculated by subtracting the reported altitudes of each ADS-B waypoint minus the elevation of the DEM at the same (x,y) position (see Beeco et al., 2020 for exact method).

To monitor change in the spatial patterns of overflights at MORU pre- and post-ATMP, the screened waypoints were analyzed in two forms. First, the waypoints, themselves, were compared across years in their original vector form. Then the waypoints were rasterized and differenced to compare areal changes in overflight patterns. All maps produced during analysis were projected to North American Datum 1983 Universal Transverse Mercator Zone 13N. All analyses that occurred were bounded to the study area (Figure 1).

## Monitoring Method Using Waypoints

The purpose of the waypoint method was to monitor the relative distance of overflight patterns to the legal boundaries (both the boundary of MORU and the “ATMP boundary” defined by NPATMA as the park boundary plus ½-mile) of the memorial pre- and post-ATMP implementation. Specifically, the signed distance ( $\pm$ ) of the ADS-B waypoints from the boundary was used to monitor change. The MORU boundary is a polygon defined in the two-dimensional x,y-plane (Figure 1). The ATMP boundary is a three-dimensional polyhedron, with its cross-section being the MORU boundary expanded by a half-mile buffer (Figure 1). The irregular upper surface of the polyhedron is located at 5,000 feet AGL, enclosing a volume of 5.9 cubic miles (24.8 cubic kilometers).

To monitor changes in overflight patterns, we define a waypoint  $p(x, y, z, t)$  at a given time  $t$  with coordinates in three-dimensional space. The *signed distance* is the shortest distance from a waypoint to the nearest legal boundary, specifically the ATMP boundary. A waypoint is considered to have a negative signed distance if it is observed within the boundary. The signed distance was normalized as a proportion of the ½-mile ATMP buffer for easier interpretation. To understand the rarity of a waypoint’s signed distance, we calculate the percentile rank of each signed distance value. A larger signed distance corresponds to a higher percentile rank, with unusually large distances approaching the 100<sup>th</sup> percentile. The Python library Geopandas v0.14.1 (Van den Bossche et al., 2023) was used to implement the signed distance waypoint methods.

To enumerate changes in overflight patterns with respect to the boundaries, the conditional probability of observing waypoints inside the boundary was calculated for a given year,  $y$ , as  $P(p_{within} | y)$ . The difference between the probabilities,  $P(p_{within} | 2024) - P(p_{within} | 2023)$ , reveals how the sign of overflight patterns changed over time. The boundary for the ATMP also includes an altitude condition, so a test of the altitude boundary is also necessary to accurately monitor change. The difference in conditional probability  $P(p_{within} | (2024 \& p < 5000 \text{ ft AGL})) - P(p_{within} | (2023 \& p < 5000 \text{ ft AGL}))$  reveals how the sign of overflight patterns changed over time.

The Ranger’s Amphitheater is both a popular viewing location of the MORU Shrine of Democracy sculpture and a location for park programs and ceremonies. For this reason, the amphitheater represents a meaningful listening location from which to estimate the beneficial change in sound level for park visitors due to the ATMP. To isolate the acoustic effect due to management action alone (i.e., the ATMP), only the points affected by the action,  $p_{within}$ , were considered. Then, for each year the mean three-dimensional slant distances from each point to the center of the amphitheater were determined. For simplicity, it is assumed that a helicopter may be treated as an acoustic point source in the free field. Then, the decrease in sound level due to the management action may be estimated to a first-order approximation using the well-known equation for geometric divergence (Cowan, 1993, Equation 3–5):

$$\Delta L = L_{2024} - L_{2023} = 20 \log_{10} \frac{d_{2023}}{d_{2024}}$$

## Monitoring Method Using Rasters

The raster method was developed to further track and visualize changes in overflight patterns over the landscape surface of the study area. Since rasters are grids of data associated with specific geographic locations, they can be compared or subtracted from each other as long as their spatial extent and the size of their cells are the same. These methods are similar to the kernel density analysis used in other ADS-B reports produced for the NPS, such as those by Peterson et al. (2024b). However, instead of grouping waypoints by altitude bins, the waypoints in this analysis are considered together across the entire range of observed altitudes.

To analyze the waypoints as rasters, the Python library Rasterio v1.3.9 (Gillies et al., 2024) was used. This library rasterized the waypoints, meaning it counted the number of waypoints within 20-meter grid cells spanning the entire study area. A 20-meter cell roughly corresponds to the distance that an aircraft is expected to travel in the 0.5-second time resolution of the ADS-B record. Such a grain choice optimizes distinctions of spatial change under the performance constraint that the overall number of cells is kept as small as possible. Waypoints from each year were rasterized separately.

Once the waypoints for each year were rasterized, the rasters for 2024 and 2023 were differenced by subtracting  $R_{2024} - R_{2023}$ . This difference reveals three possible conditions: (1) zero difference, when the values of the rasters are identical, indicating no change in point density; (2) positive difference, when the value for 2024 was greater than for 2023, indicating an increase in point density; (3) negative difference, when the value for 2024 is less than for 2023, indicating a decrease in point density.

A spatial autocorrelation metric, Moran's  $I$ , was also calculated from the difference raster. Moran's  $I$  is a measure of the overall clustering of spatial data, useful to support reasoning about systematic change in a transportation network. Values of Moran's  $I$  that are close to +1 indicate that similar values tend to cluster together. Values close to -1 indicate that similar values tend to be spatially dispersed. Values close to zero suggest no spatial autocorrelation. Because rotorcraft overflights can change heading over short distances, the appropriate form of adjacency for calculating the Moran's  $I$  spatial weights matrix is Queen's case contiguity (e.g., both edges and corners are considered adjacent; Fotheringham and Rogerson, 2008, §8.1.3).

## Attribution of Cause

By design, the analysis of change in this study is primarily associative in nature and focused on revealing changes to spatiotemporal patterns based on observed data. While differences in conditional probability or point density may reveal changing patterns in the data, they can never solely confirm the causal mechanisms behind those changes (Pearl, 2009). To correctly attribute an observed change to a particular causal mechanism, a decisionmaker must structure relevant knowledge of causal mechanisms into a network graph (Pearl, 1988).

In such a causal graph, we may encounter a *collider*—a resulting variable that is known to be influenced by two or more factors, such as a management action and an external factor like weather or visitation conditions (Kelter, 2022). The presence of a collider complicates the attribution of cause

because it can create a spurious correlation between the influencing factors. In other words, if both management action and external factors contribute to the actual outcome, such a collider “blocks” the direct attribution of cause to a single factor.

In this context, counterfactual reasoning helps to clarify whether a collider could be present in the causal graph. If not, the observed change can be reasonably attributed to management action, alone. For each of the main associative results, an attempt to generate relevant counterfactual claims was made. If no prominent counterfactual claim was apparent, the ADS-B observations, alone, were considered sufficient to attribute cause to the ATMP. If a prominent counterfactual claim was apparent, the ADS-B observations were considered insufficient for causal attribution.

# Results

## Results: Waypoint

The map of screened waypoints for all flights (Figure 2) reveals the air transportation network above and near MORU in 2023 and 2024. Each waypoint is plotted with 99.0% transparency, so components of the network with concentrated opaque lines indicate where there is appreciable flight density. The directional flow of aircraft along their routes is traced through a cyclic colormap (north = 0 or 360 degrees, east = 90 degrees, south = 180 degrees, and west = 270 degrees). The network shares the ring-like pattern observed in 2020 and 2021 (Peterson et al., 2022). The most spatially complex region of the network is to the southeast of MORU, where the Shrine of Democracy is best visible from the air. In 2023, 107 aircraft transmitting ADS-B signals flew near the park within the study period, averaging 19 flights per day. In 2024 there were 163 aircraft, averaging 16 flights per day. In both sets combined, there were a total of 257 unique aircraft observed, but only 13 observed in both records. These 13 aircraft represented 77% of the waypoints in 2023 and 85% in 2024. A further subset of 7 rotorcraft represented 72% of the observed waypoints overall in 2023 and 82% in 2024.

The synopsis of spatial change from 2023 to 2024 that is visible in Figure 2 is quantified by numeric indicators, provided in Table 1. The overall number of screened waypoints determined using the ADS-B toolbox were similar, 786,156 and 760,631 in 2023 and 2024, respectively. The difference of -22,525 points represents a -3.2% reduction across years.

At the scale of the study area, the number of points contained within the ATMP legal boundary's x,y-cross section was 184,519 and 82,982 in 2023 and 2024, respectively. Over the entire study area, the difference in conditional probabilities  $P(p_{within} | 2024) - P(p_{within} | 2023)$  was -12.6%. The number of points within the entire polyhedral ATMP boundary was identical to the number of points within the x,y-cross section. So, too, was the difference in conditional probabilities  $P(p_{within} | (2024 \& p < 5000 \text{ ft AGL})) - P(p_{within} | (2023 \& p < 5000 \text{ ft AGL}))$  at -12.6%. The number of points within the MORU boundary was 52,104 and 3,439 in 2023 and 2024, respectively. The difference in conditional probabilities  $P(p_{within} | 2024) - P(p_{within} | 2023)$  was -6.2%.

At the scale of the ATMP boundary, the corresponding probabilities are equal to -55.0%, -55.0% and -93.4%. The mean signed distance for the 2024 set of waypoints  $p_{within}$  was -788 feet (29.5% into) the 1/2-mile buffer. The mean signed distance corresponded to the 66<sup>th</sup> percentile rank. The signed distance of -2640 feet (e.g., the 1/2-mile to the MORU boundary, itself) corresponded to the 95<sup>th</sup> percentile rank. In 2023 the mean and 95<sup>th</sup> percentile signed distances were -1809 and -4142 feet.

The mean absolute three-dimensional distance from the Ranger's Amphitheater to waypoints  $p_{within}$  was 5339 and 7396 feet (+2057 feet). In other words, the average distance of a point from the Ranger's Amphitheater increased nearly 0.4 miles from 2023 to 2024. The difference in maximum sound level,  $L_{eq,1s} [12.5-20000 \text{ Hz}]$  corresponding to this change in offset was  $\Delta L = -2.8 \text{ dB}$  for a typical overflight.

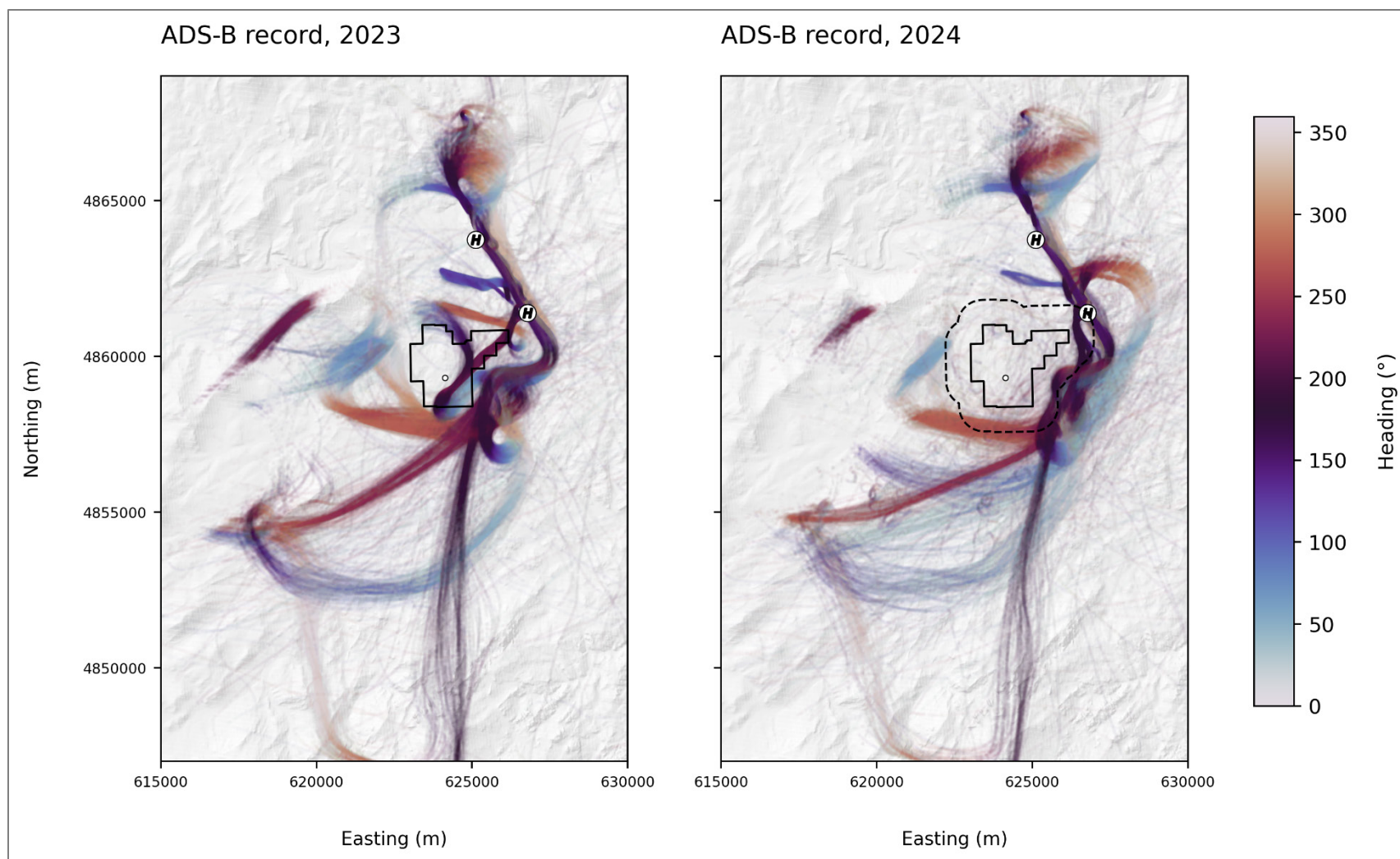


**Figure 2.** Waypoints from flights over and near MORU from May 15<sup>th</sup> to June 25<sup>th</sup>, flying between 0 and 9,000 feet MSL. Observations from 2023 (left) and 2024 (right) are colored by aircraft heading (north = 0 or 360 degrees, east = 90 degrees, south = 180 degrees, and west = 270 degrees). The ADS-B logger is indicated by a point (white) within MORU boundary (black). The local helipads (“H”) and ATMP legal boundary (dashed) are included to contextualize the 2024 observations. Points are plotted with 99.0% transparency.

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**Table 1.** Waypoint spatial changes from 2023 to 2024 at the boundary and study area scale.

| Indicator                                                    | 2023 Value | 2024 Value | Boundary Change | Area Change |
|--------------------------------------------------------------|------------|------------|-----------------|-------------|
| Overall waypoints                                            | 786,156    | 760,631    | N/A             | -3.2%       |
| Waypoints within ATMP x,y-cross section                      | 184,519    | 82,982     | -55.0%          | -12.6%      |
| Waypoints within ATMP legal boundary (x, y, z)               | 184,519    | 82,982     | -55.0%          | -12.6%      |
| Waypoints within MORU boundary                               | 52,104     | 3,439      | -93.4%          | -6.2%       |
| Mean signed distance to ATMP boundary                        | -1809 feet | -788 feet  | +1502 feet      | N/A         |
| 95 <sup>th</sup> percentile signed distance to ATMP boundary | -4142 feet | -2640 feet | +1021 feet      | N/A         |
| Mean slant distance from Ranger's Amphitheater               | 5339 feet  | 7396 feet  | +2057 feet      | N/A         |

### Results: Raster

The map of point density difference visualized as a raster (Figure 3) clarifies changes in overflight patterns over the surface of the study area. At a fine grain of 20 m<sup>2</sup>, the study area raster had a total of 825,000 cells. No change in density occurred between years in 589,101 cells (71.4%). Point density increased in 118,151 cells (14.3%) and decreased in 117,748 (14.3%). Within the ATMP boundary there were a total of 40,016 cells. In 12,975 (32.4%) of these cells no change in density occurred. Point density increased in 6,101 cells (15.2%) and decreased in 20,940 (52.3%). Moran's  $I = 0.61$  ( $p = 0.001$ ) was determined for the difference raster and indicates moderately strong spatial clustering, with areas of greater waypoint density change occurring near one another. This reflects the continuity of flight paths across the landscape.

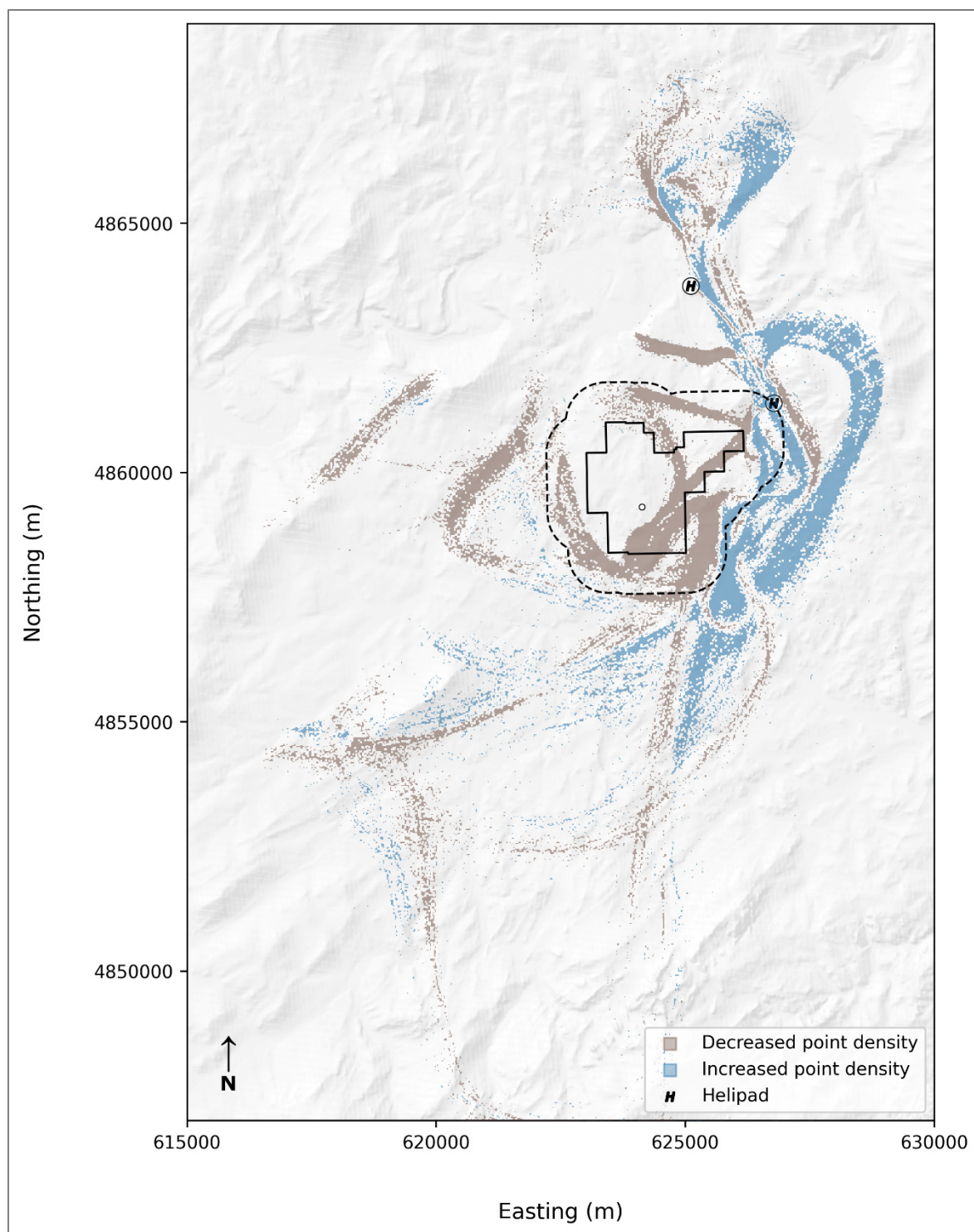


**Figure 3.** The point density difference for 2023 and 2024 visualized as a raster. Cells are colored by their direction of change. Decreasing density is brown, increasing density is blue. If no change occurred, the cell is transparent. The ADS-B logger is indicated by a point (white) within MORU boundary (solid black). The ATMP legal boundary (dashed) is included to contextualize the change. Helipad locations within the study area are indicated by an “H”.

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## Discussion

This study used ADS-B data collected from May 15<sup>th</sup> to June 25<sup>th</sup> in 2023 and 2024 to monitor changes in overflight patterns and consider which, if any, of these changes are attributable to the MORU ATMP. The MORU ATMP had an effective date of May 13, 2024. The ATMP, which prohibits air tours within ½-mile of the boundary of MORU (also known as the ATMP boundary), required major changes to air tour travel patterns that existed prior—these changes were not considered reasonably foreseeable during the ATMP development. To monitor change in overflight patterns, novel waypoint and raster methods were developed. A discussion of the observed changes and their potential for causal attribution follows. Of central importance to the reasoning is the fact that any attributable changes to overflight patterns reflect the innovative, self-organized response of the operators, which was in no way specified by the ATMP.

In 2023, the three-dimensional pattern of overflights was found to be generally identical to the initial MORU ADS-B dataset, 2020–2021 (Peterson et al., 2022). In contrast, the paired sets of ADS-B waypoints from 2023 and 2024 reveal a pronounced change to spatial patterns above and in the surrounding area of MORU. The data provide evidence that the overflight pattern around MORU primarily emerges from the activity of 13 aircraft—accounting for 77% and 85% of the waypoints in 2023 and 2024, respectively. A further subset of these 13 aircraft found 7 rotorcraft aircraft accounted for  $\geq 70\%$  of observed waypoints in both years, with a proportional noise exposure change expected.

Waypoint analysis revealed three notable quantitative changes in the ADS-B record between 2023 and 2024. First, a  $-3.2\%$  change in the overall number of waypoints was observed—indicating that there was not a dramatic change in the number of points between years. Second, a distinct spatial shift away from the park: a  $-93.4\%$  change in waypoints within the planar area of the MORU boundary and a  $-55.0\%$  change in waypoints within the ATMP legal boundary volume. Third, the signed distance from both the ATMP legal boundary (mean +1502 feet, 95<sup>th</sup> percentile +1021 feet) and the Ranger’s Amphitheater (mean +2057 feet) increased.

Raster analysis (Figure 3) revealed the extent of the self-organized spatial change. Flight density was found to be unchanged over the majority (71.4%) of the study area. Density changes elsewhere were approximately balanced—with 14.3% of raster cells increasing and an equal percentage decreasing—indicating a new, spatially stable configuration without net diffusion or concentration. Again, an indication that the overall number of points did not drastically change between years but rather moved spatially. This outcome is notable: such a balanced transformation was not inevitable. The system could easily have drifted toward greater concentration or random dispersion. Instead, operators collectively shifted to a pattern that maintained overall spatial balance. The moderate, positive  $I$  over the entire study area (0.61) supports this interpretation, suggesting that the restructuring was spatially coherent and organized, rather than diffuse or random.

These results are consistent with the broader principles of route formation in self-organized human transportation systems (Helbing et al. 1997, Xie and Levinson 2011). Air tours, constrained by both

fixed origins and operational limits, tend to naturally form loop-like patterns. These loops emerge neither from diffusive exploration nor redundant transport needs, but from the spatial necessity of returning to base, paired with attraction toward scenic vistas (e.g., the Shrine of Democracy). The resulting routes reflect a stable balance between anchoring (the helibase) and attraction (the scenic symbol) forces, giving rise to habitual routing paths. Such patterns, while emergent and flexible, leave measurable traces of their internal stability—a stability that remains evident in the airspace around MORU following the implementation of the ATMP.

### **Patterns of Change as Related to the ATMP**

The purpose of this report is not to perform a compliance check with the Air Tour Management Plan (ATMP), but the analysis presented here does merit some discussion. Figures 2 and 3 illustrate air tour travel patterns for 2024 that align with the ATMP. Notably, the 2023 patterns within the ATMP boundary are absent in the 2024 data.

A closer examination of Figure 3 reveals an increase in air traffic within the ATMP boundary along the eastern edge in 2024. Much of this activity, especially in the northeastern corner, is likely related to departures and arrivals at the heliport situated at the boundary of the ATMP. The ATMP allows for certain flight segments that are “solely for the purposes of takeoff or landing.” In contrast, the data from the southwestern portion of the ATMP boundary may require a more detailed compliance analysis in the future. Overall, the analysis suggests that the ATMP is effectively moving air tours further away from park resources, thereby benefiting the park’s acoustic environment.

### **Causal Attribution of Change**

Next, we consider which, if any, of the observed changes were likely to have been caused by the ATMP. Importantly, because the same ADS-B logger was deployed in precisely the same position and orientation in both years, detection uncertainty was scientifically controlled and cannot influence attribution. By eliminating detection as a causal factor, there remain three prominent counterfactual claims:

1. Overall MORU visitation decreased between May and June 2023 and the same months in 2024: 956,424 → 676,062, a –29.3% change (NPS, 2025).
2. There was twice the precipitation volume in the Mount Rushmore forecast area in 2023 as occurred in 2024: 11.0" → 5.2". Otherwise, the weather was similar during both periods of observation (NWS 2025).
3. The waypoint screening response of ADS-B Tool #4 depends on the inverse sinuosity of each flight path. The default behavior was used in this analysis, rejecting paths that were effectively straight lines,  $\geq 99\%$  linear (Hutchinson and Peterson 2024).

Given these counterfactual claims, the overall change in ADS-B waypoint count must be considered a collider variable. For this reason, the observed –3.2% change in total waypoints across the study area cannot reasonably be attributed to the ATMP. Reduced visitation, for instance, could also have caused fewer flights to occur, and thus a decline in total waypoints. Reduced precipitation could have improved flying conditions and caused more flights to occur, contradicting the observed decrease.

Although it has been established that air tours currently form a sinuous loop around MORU, part of the observed decrease may also have been caused by non-local aviation patterns becoming more linear, increasing the number of flights filtered and a corresponding decline in the total waypoints.

In contrast, the other two major spatial shifts in waypoints—those outside the boundaries and those away from the Ranger’s Amphitheater—can reasonably be attributed to the ATMP. No prominent counterfactual claim is available to explain such large changes in conditional probability and signed distance. Changes in visitation do not causally affect aircraft position, nor does the shape of an overflight pattern affect its absolute position in space. Weather does change overflight routing in some scenarios; however, it is extremely unlikely that dangerous weather conditions repeatedly developed directly over the park in 2023 and not in 2024. So, the ATMP is most likely responsible for the observed reorganization of overflight patterns.

The estimated acoustic benefit of the ATMP to visitors in the Ranger’s Amphitheater was  $\Delta L_{eq,1s} [12.5-20000 \text{ Hz}] = -2.8 \text{ dB}$  for a typical overflight—potentially doubling active space (communication space) for visitors compared to pre-ATMP conditions. In practice, this means that an interpreter giving a program at the Ranger’s Amphitheater could be heard clearly at twice the distance as before. Another interpretation of a reduction of  $-2.8 \text{ dB}$  is that this is nearly the equivalent of a reduction of 50% in air tours over the park.

## Conclusion

This study evaluated whether overflights around Mount Rushmore National Memorial (MORU) responded to the implementation of the park's Air Tour Management Plan (ATMP), and if so, how such a response manifested spatially. Using newly developed waypoint and raster methods, we found strong evidence of a spatial reorganization between 2023 and 2024. This shift was driven primarily by a small group of commercial air tour operators and involved an acoustically restorative displacement of flight paths away from the ATMP legal boundary and the Rangers Amphitheater resulting in a corresponding reduction of air tour noise.

Because the ATMP imposed no specific routing prescriptions, the observed changes reflect a decentralized, self-organized response to the plan. It was found that confounding factors such as visitation trends, weather, and aircraft flight path morphology block causal attribution of the change in total waypoint count to ATMP implementation. However, there is no apparent counterfactual claim which could account for the magnitude nor specificity of the spatial shifts in aircraft locations observed. Causal attribution to the ATMP is therefore reasonable and supported by the evidence for the spatial shifts.

The resulting flight density patterns revealed a balanced spatial equilibrium—a finding that suggests the potential for stable, adaptive reconfiguration in response to the constraint of the ATMP. In other words, these results suggest that while the ATMP changed the local spatial patterns of flights, it did not change the number of waypoints logged (a proxy for flight time). The results of this study may offer insight into not only local planning outcomes at MORU but also the underlying dynamics of air tour loop patterns in general. Future research should examine whether such equilibria arise in similar mitigation contexts and whether they can be anticipated as part of a scientifically informed framework for managing airspace-related noise.

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