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Night Sky Explorer VR

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Abstract

Artificial light at night (ALAN) degrades nocturnal ecosystems and complicates astronomical observation. Although all-sky imaging and GIS-based light-pollution mapping are well established in the analysis of light pollution, identifying local contributors to ALAN still requires time-consuming cross-comparisons, done in separate views, making light halo–source attribution slow and manual. We present an interactive system that addresses this gap by co-registering Sky Quality Camera all-sky imagery and OSM-derived candidate emitters (e.g., settlements, roads, aerodromes, industrial sites) in one observer-centered scene. The viewer is placed at the locations of the captured all-sky images in 3D digital terrain model-based scenes, realistically illuminated by the sky under selected conditions for an immersive view of nighttime scenarios. OpenStreetMap features are projected onto a surrounding sphere via inverse stereographic projection, with point markers and horizontal-extent indicators to support rapid visual matching between observed halos and plausible sources. Users can switch scenes and processed sky images, adjust projection parameters, and inspect scenes in VR or in an additional cylindrical projection for a panoramic desktop view. A companion web tool configures location classes and display ranges. The presented system primarily targets exploratory analysis, with its main contribution being the novel co-visualization of light sources and light halos; expert interviews positively validated this analytical focus. As a secondary outcome, the system’s immersive first-person representation may also enrich educational communication and outreach on ALAN impacts.

1. Introduction

Artificial light at night (ALAN) affects several domains at once: it degrades the quality of astronomical observations by brightening the background sky, disrupts nocturnal ecosystems by altering natural light-dark cycles, and is increasingly discussed as a factor that can influence human health and well-being (Sanders et al., 2021, Schulte-Römer et al., 2019). As a result, there is a growing need not only to measure how bright the night sky is at a given location, but also to understand *why* it is bright in particular directions and how different sources contribute to the overall skyglow. In other words, mitigation efforts require moving beyond simple global or regional indicators of light pollution, such as averaged radiance values from satellite sensors, toward methods that reveal the role of individual cities, industrial zones, transport corridors, or isolated facilities in shaping what an observer actually sees in the sky (Barentine, 2022, Widmer et al., 2022, Deverchère et al., 2022).

All-sky imaging approaches have emerged as a particularly useful tool in this context. Systems based on calibrated digital cameras and automated processing pipelines capture the full celestial hemisphere in a single exposure, and convert these images into luminance or radiance maps expressed in physical or perceptual units (Jechow et al., 2019b, Kolláth and Dömény, 2017, Jechow et al., 2019a). These maps make it possible to quantify spatial variations of sky brightness across the dome, to compare clear and cloudy conditions, and to isolate artificial components by subtracting the natural sky background. For a given observation site, they therefore provide a detailed, observer-centric picture of how bright the sky is in each direction.

However, even with such rich hemispherical data, identifying the terrestrial sources responsible for specific bright regions in the sky remains challenging in practice. Analysts often need to manually compare the patterns seen in all-sky images with external maps, satellite radiance products, and local knowledge about surrounding settlements and infrastructure. This typically requires manual cross-referencing across multiple software tools and coordinate systems, mentally aligning bright skyglow patches (halos) with plausible emitters on 2D maps or in GIS. As a result, linking skyglow structures in all-sky images to their actual sources on the ground is still a time-consuming and cognitively demanding task.

In practice, experts frequently combine several information sources: (i) all-sky images or derived luminance maps; (ii) remote-sensing products such as Visible Infrared Imaging Radiometer Suite - Day/Night Band (VIIRS-DNB) satellite radiance maps (Miller et al., 2013); and (iii) geographic information system (GIS) layers describing settlements, road networks and other potential emitters. Establishing which city, industrial site, or traffic corridor is responsible for a given halo in the sky typically involves repeated cross-referencing among 2D maps, tabular attribute views and different projections of hemispherical imagery, mentally assembling a 3D picture of the environment. This workflow not only introduces cognitive overhead, but also complicates communication with non-specialists such as local decision-makers or park managers who may be unfamiliar with technical cartographic products.

Immersive and three-dimensional geovisualization have been demonstrated to support such spatial reasoning tasks. Multi-perspective geovirtual environments for city and landscape analysis are reported in (Lorenz et al., 2008, Pasewaldt et al., 2014), while planning-oriented 3D city visualization workflows are described in (Brasebin et al., 2016, Buyuksalih et al., 2017). Outdoor AR work introduces extended overviews and occlusion handling for in-situ environmental interpretation (Veas et al., 2012). In immersive analytics, IATK (Cordeil et al., 2019) and DXR (Sicat et al., 2018) provide VR-oriented toolkits for interactive spatial data exploration.

Across these systems, a recurring challenge is how to preserve local detail together with global context. Focus+context and multi-perspective strategies address this through controlled geometric deformation and spatially varying projections, including sigma lenses (Pietriga et al., 2009), complex-logarithmic mappings (Böttger et al., 2008), stereographic variants (Shenk et al., 1971), and multiperspective camera models (Wu and Popescu, 2017). Within this family, the inverse stereographic “virtual data sphere” is particularly relevant to our work: it lifts surrounding terrain and map context onto a sphere around the observer and has been shown to support exploratory VR navigation and comparison tasks (Spur et al., 2022). Section 2 provides a detailed discussion of these strands and how they relate to our implementation.

In this paper, we apply the inverse stereographic projection to the analysis and communication of ALAN. We present an interactive application that co-registers calibrated all-sky images with a digital terrain model and OpenStreetMap (OSM) features (Ope, 2024) in an immersive VR environment. Potential contributors to skyglow—such as cities, villages, aerodromes, industrial sites and military bases—are projected onto a surrounding sphere and represented by markers with angular-extent indicators, enabling rapid identification of plausible emitters for observed halos. A companion web tool prepares OSM-based location data, outlines and angular arcs around an observation point, while a configurable cylindrical reprojection supports desktop-based inspection of the same scene.

The current implementation is limited to a set of preprocessed, static observation locations with pre-recorded all-sky images. Users can compare and inspect these locations quickly and move around their associated 3D environments within limits, but arbitrary location exploration is left for future extensions and will build on in-development simulation tools (Dobashi et al., 2023).

The contributions of this work are:

- An integrated system that combines calibrated all-sky imagery, 3D terrain, and OSM-derived potential light sources in an inverse stereographic projection tailored to ALAN analysis.
- A web-based preprocessing tool that derives outlines and angular extents for candidate emitters from OSM data around a chosen observation point, exporting JSON descriptions for use in the immersive visualization.
- A dual-mode visualization pipeline that offers the choice between an immersive view in virtual reality and a cylindrical projection optimized for desktop-based exploration.
- An initial expert-based evaluation with two specialists in lighting and light pollution, providing qualitative feedback on the analytical value and communication potential of the approach.

By situating skyglow patterns in a first-person, georeferenced context and explicitly encoding the angular footprint of potential emitters, the proposed system aims to reduce the effort required to link visible halos to their terrestrial sources, while also serving as a pedagogical tool for illustrating the impacts of ALAN to a broader audience.

2. Related Work

This section discusses and organizes the prior work mentioned above by its role in our presented system: XR geovisualization infrastructure, focus+context projection design, and ALAN imaging/monitoring and communication studies. For each strand, we clarify what our implementation reuses and where the present work adds a new combination.

2.1 XR in Geovisualization

Recent advances in extended reality (XR) have produced a broad set of immersive geovisualization systems for environmental and urban applications. A recurring theme in this literature is infrastructure: how to connect GIS data processing and immersive rendering pipelines. Game engines such as Unity and Unreal are increasingly used as front-ends for GIS workflows, enabling interactive 3D exploration of terrain, city models and environmental data in VR and AR. An integrated QGIS-to-Unreal workflow has been reported for VR/AR visualization of digital elevation models and thematic layers (Pavelka Jr and Landa, 2024), illustrating both practical integration steps and the interpretive value of immersive perspectives.

Web-based approaches emphasize collaborative access to simulation outputs. GeospatialVR, for example, streams environmental simulation results into shared virtual environments where multiple users can explore scenarios such as flood processes together (Sermet and Demir, 2022). Earlier Unity-based systems for interactive 3D city visualization and planning support (Buyuksalih et al., 2017, Brasebin et al., 2016), as well as immersive analytics toolkits such as IATK and DXR (Cordeil et al., 2019, Sicat et al., 2018), further show that reusable XR components can host heterogeneous geospatial and analytical data.

In parallel, geospatial platforms such as Cesium provide efficient 3D tiling and streaming of global terrain, imagery and vector data for XR applications. Taken together, these developments establish a robust technical foundation for domain-specific immersive systems that integrate multiple geospatial data layers in one environment.

Our implementation in Section 3 builds directly on this infrastructure layer: Unity/OpenXR runtime, streamed geospatial context, and interactive 3D exploration. The novel part of the present paper is not a new generic XR stack, but a task-specific composition for ALAN analysis that combines this stack with calibrated all-sky imagery and explicit candidate-source overlays.

2.2 Focus+Context and Multi-Perspective Visualization

Our approach is also rooted in focus+context and multi-perspective visualization, where the central objective is to preserve global orientation while enabling local inspection. In 2D, sigma lenses provide representation-independent in-place magnification through smooth deformations (Pietriga et al., 2009),

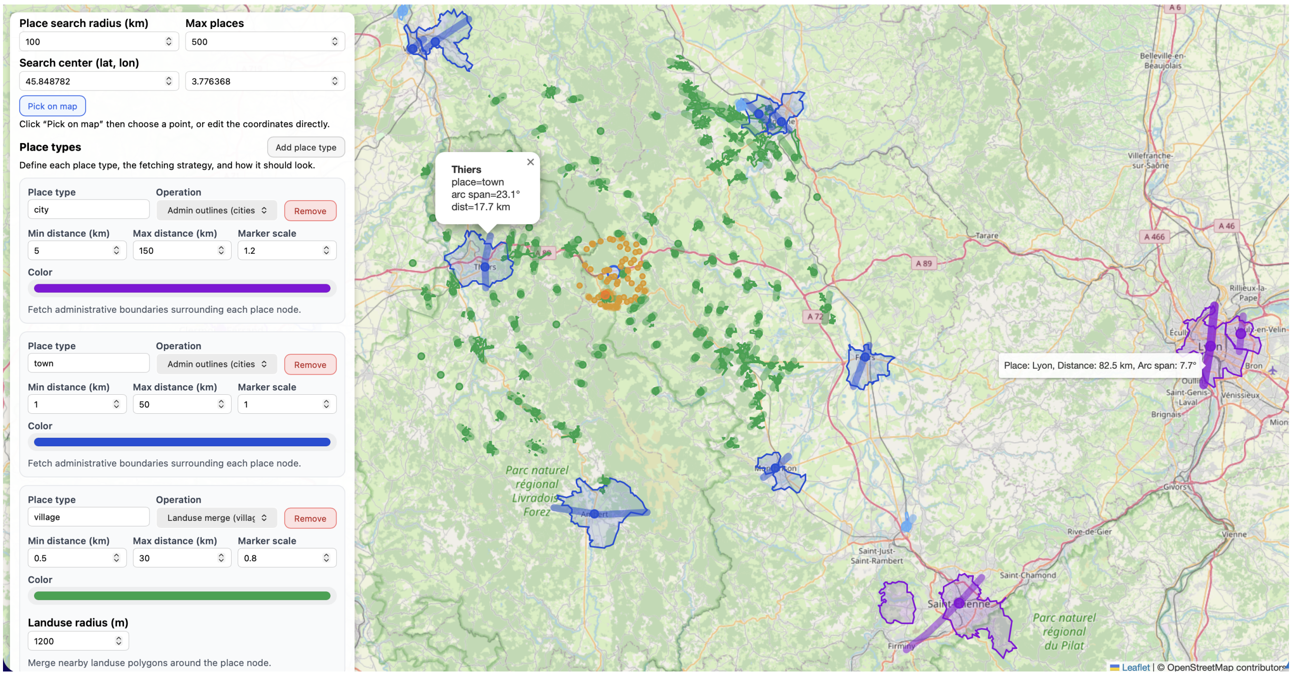

Figure 1. Example view of the companion website, visualizing nearby locations fetched according to the specifications of each location type.

and complex-logarithmic mappings produce detail-in-context views for satellite imagery (Böttger et al., 2008).

In geospatial 3D and AR/VR, this objective appears in multi-perspective terrain and panorama techniques that combine local and global context within one image (Lorenz et al., 2008, Pasewaldt et al., 2014), in extended-overview AR approaches that add elevated views to first-person outdoor viewpoints (Veas et al., 2012), and in multiperspective camera/occlusion-management strategies for navigation tasks (Wu and Popescu, 2017). Recent immersive focus+context interfaces, including portal widgets (Han et al., 2022) and multi-focus probes (Zimmermann and Bruckner, 2025), continue this line by embedding local detail views directly in VR space.

Within this family, the inverse stereographic projection (Spur et al., 2022) is particularly relevant to our design and can be connected to related cartographic projection ideas (Shenk et al., 1971). It places the observer at the center of a spherical projection surface and uses a conformal stereographic mapping from the zenith to lift surrounding terrain and map content into view. In this paper, we build on that projection for the ALAN use case by relating skyglow effects to potential terrestrial sources, and we add a secondary cylindrical transformation for panoramic desktop inspection.

2.3 Light Pollution and All-Sky Visualization

ALAN and the associated skyglow have received increasing attention in recent years, both as an environmental stressor and as a topic of public interest. Citizen-science analyses indicate rapid worldwide degradation of star visibility and suggest strong annual increases in effective sky brightness in many regions, by up to several percent per year (Kyba et al., 2023). This motivates methods that not only quantify sky brightness, but also connect directional skyglow patterns to concrete terrestrial sources.

Calibrated all-sky imaging is a key empirical basis for this task. Workflows based on panoramic fisheye acquisition provide radiance/luminance characterization for ecological light-pollution studies (Jechow et al., 2019b). Dark-sky monitoring workflows based on Sky Quality Camera provide operational quality-assessment pipelines for protected areas (Kolláth and Dömény, 2017). Differential all-sky photometry supports separation of natural and artificial components under different cloud conditions (Jechow et al., 2019a). Together, these approaches cover complementary tasks, from baseline characterization to operational monitoring and component separation.

At larger scales, VIIRS-DNB satellite observations provide global nocturnal radiance products for regional monitoring (Miller et al., 2013). For simulation, physically based methods can compute interactive night-sky brightness distributions from emission patterns and atmospheric scattering (Dobashi et al., 2023). Communication-oriented studies add another perspective: VR-based environments have been explored for evaluating lighting-design alternatives (Krupiński, 2020), and expert surveys report both shared and diverging perspectives between lighting professionals and light-pollution experts (Schulte-Römer et al., 2019).

These strands are complementary in scale and purpose, but in practice they are often still viewed in separate representations. Existing analysis workflows commonly inspect sky brightness as hemispherical plots or static panoramas and then manually cross-reference external maps or GIS to infer candidate emitters. Our system builds on the same measurement and mapping inputs, but contributes a tighter integration: calibrated all-sky imagery and OpenStreetMap-derived emitters are brought into one immersive, observer-centric environment. By projecting potential sources onto a surrounding sphere and encoding their angular extent relative to the observer, our approach directly supports the task of matching skyglow structures to terrestrial sources, while complementing existing ALAN mapping and simulation tools with an experiential VR perspective.

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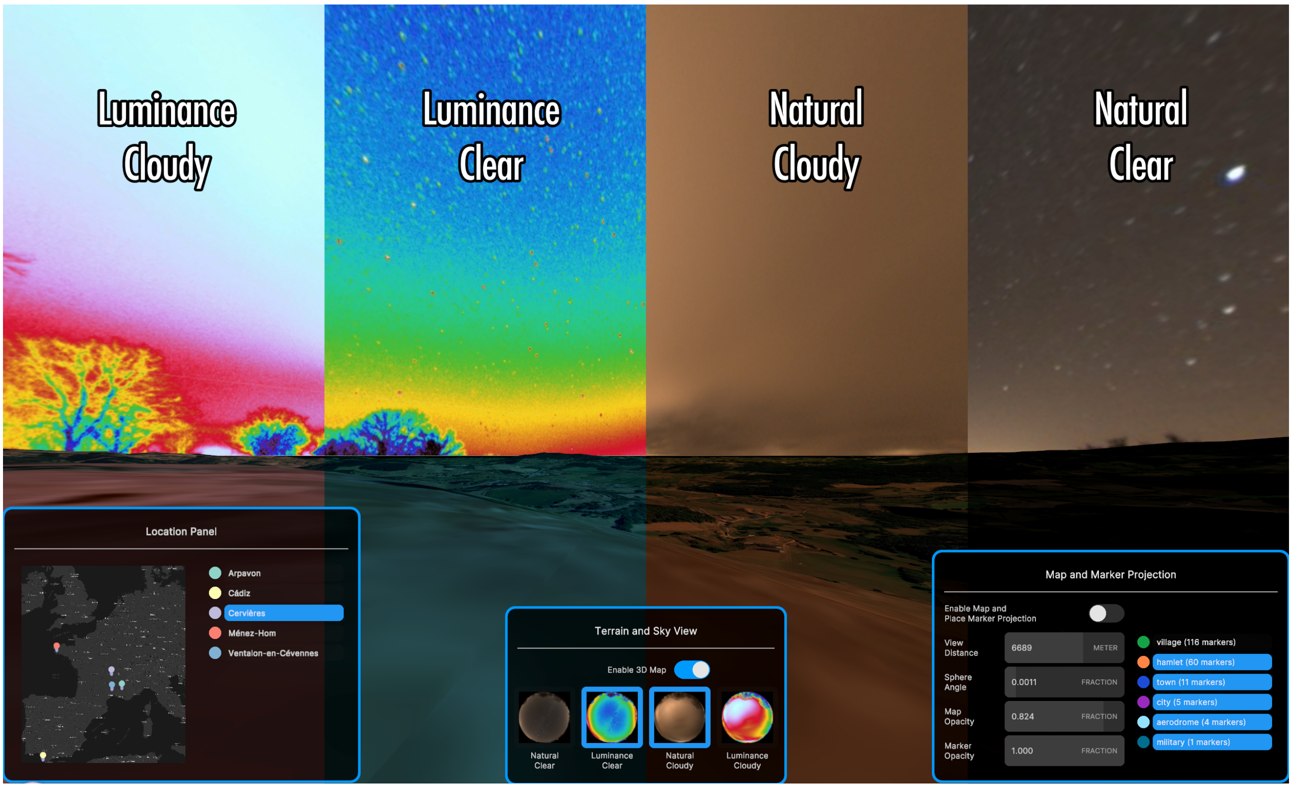

Figure 2. Split views of four different all-sky images illuminating a digital terrain model.

3. System Overview

3.1 Data and Tools

The application is built in the Unity engine[1], uses OpenXR, and targets high-resolution VR HMDs such as the Meta Quest 3 or better. It integrates Cesium[2] for photorealistic 3D tiles (textures and elevation from Google Earth (Kawai, 2024)), Bing road maps, and OpenStreetMap's Overpass API[3] for location markers, within a custom immersive visualization interface.

3.1.1 Location Data To support the immersive application, we developed a companion web tool that prepares OpenStreetMap-based location data, outlines, and arc descriptors for offline VR use (Figure 1). The tool is a client-side web application built with Leaflet for interactive mapping, plus Overpass queries, osmtogeojson, and Turf.js for data conversion and geometric processing. Users specify an observation point, search radius, and feature classes to include (e.g. cities, towns, villages, hamlets, suburbs, aerodromes, military bases, and selected land-use categories). The interface issues targeted Overpass QL queries around the observation point, filters and ranks returned nodes by distance and type-specific thresholds, and visualizes selected locations as interactive markers on a base map.

For locations that are mapped with meaningful administrative boundaries (primarily cities and towns), the tool retrieves the corresponding boundary relations and ways and converts them into polygonal outlines. For smaller settlements and non-administrative objects (villages, hamlets, suburbs, neighborhoods, aerodromes, military bases), the tool instead queries surrounding land-use polygons or aerodrome/military features within configurable radii and unions them into a single footprint per location.

In a final step, the tool derives “outline arcs” that summarize, for each location, the angular span under which it appears from the chosen observation point. All polygon coordinates are re-expressed relative to the observer, and the bearings to the polygon vertices are collapsed into one or more angular intervals, optionally split when large gaps exceed a user-defined threshold. The complete result for each location—identifier, name, type, distance, outline geometry, and one or more arc segments—is exported as a compact JSON file.

3.1.2 All-sky Images For each location dataset, we use all-sky nighttime images captured by DarkSkyLab (Dar, n.d.) and processed with Sky Quality Camera (SQC, Euromix Ltd, Ljubljana, Slovenia), software for calibrated digital-camera imagery (Jechow et al., 2019b). Each location includes clear and cloudy/overcast captures, each shown in natural and SQC luminance views. The luminance rendering follows fixed false-color scale bars (provided in SQC for compatibility with earlier all-sky workflows), and similar conventions are widely used in all-sky photometry publications and operational reporting (Jechow et al., 2019a, Levin et al., 2024). We preserve this mapping for comparability with existing analyses. It supports rapid visual halo matching, but rainbow-like palettes can introduce non-uniform perceptual contrast and may overemphasize or hide gradients in some ranges (Borland and Taylor, 2007, Crameri et al., 2020). We therefore treat colors as a qualitative guide and use calibrated luminance values plus the associated legend for quantitative interpretation. SQC also offers the option to isolate artificial skyglow by subtracting celestial bodies such as the Milky Way or bright stars (Jechow et al., 2019a).

These all-sky images are stored as square image files containing

[1] Unity Technologies: Unity Engine
[2] Cesium GS, Inc.: Real-World 3D Geospatial Capability for Unity
[3] Overpass API — OpenStreetMap Wiki

a 180-degree field-of-view fisheye view. A custom shader in Unity takes a selected image and transforms it into a skybox to provide a complete 360-degree dome panorama.

To provide the bottom half of the full spherical panorama, we load photorealistic 3D tiles from Google Maps through the Cesium Ion Unity plugin. The skybox is configured to illuminate the terrain, providing a realistic view of the environment under natural-sky views and a brighter appearance under luminance views (Figure 2).

Through a floating menu, users can choose which of the available locations to explore. All available locations are also shown with a pin on a map, next to the list of locations. A second menu lets the user choose the all-sky image, with a preview and a toggle for the 3D terrain.

3.2 Inverse Stereographic Projection

To visualize the potential sources of light pollution corresponding to observed skyglow, we project the road maps and location markers (e.g. villages, cities) onto a surrounding sphere using the inverse of the stereographic projection. This method is based on multi-perspective geovisualization that aims to create a focus+context view through gentle geometric deformation (Spur et al., 2022).

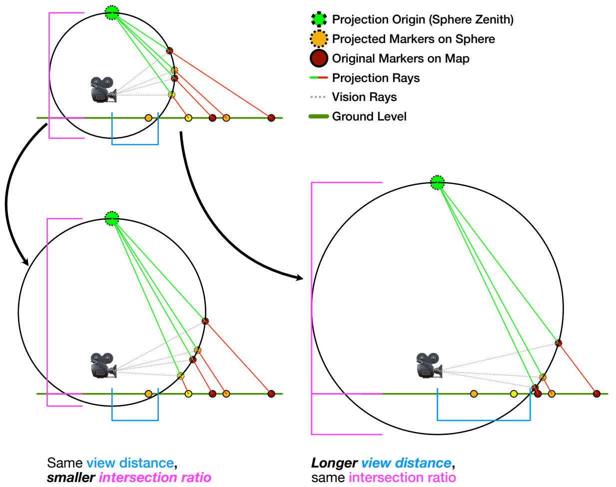

Figure 3. Illustration of the stereographic projection with different parameters for view distance and intersection ratio.

Figure 3 illustrates the principle: a sphere is created around the viewer, with its vertical axis passing through the viewer. From the sphere’s zenith, rays are cast to the ground and the markers on it. The markers are projected where these rays intersect with the sphere’s surface. The same principle applies to maps made of vectors and bitmap textures.

The projection causes the map and markers to curve upwards from the landscape, surrounding the user. Markers that would otherwise lie hidden behind hills, behind the horizon, or clumped together because of perspective foreshortening become visible, and their vertical position indicates their distance from the viewer—objects projected higher up are further away. Projection parameters are adjustable in real time, allowing users to account for different geographies and desired effects, such as stronger compression of distances or better separation of locations (Figures 4 and 3).

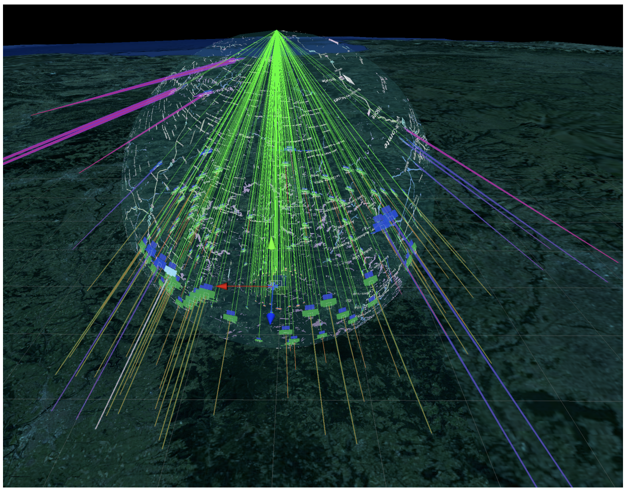

Figure 4. Example external view of the inverse stereographic projection, showing connections between the zenith and the original locations, with their projection on the sphere.

Road maps are rendered transparently with a shader that only leaves labels, roads, and mountain ranges visible. The location markers consist of a label with the location’s name, a label with the distance from the viewer, a line connecting it to its original position before the projection, and a horizontal arc showing the portion of the horizon occupied by that location’s angular extent, as calculated by its OSM outline. Except for the distance label, all other elements are colored according to the type of place. This color is set in the companion website and is also used in the third floating menu. In that menu, each location type can be toggled to reduce clutter or highlight only certain types.

The position of each marker is calculated according to the 3D inverse stereographic formula (Spur et al., 2022), with additional billboarding and scaling to ensure that it always faces the viewer and remains legible. The projection of the road map tiles is implemented using a Unity shader graph, enabling real-time adjustments without impacting performance even in a standalone VR headset.

The fundamental parameters of the projection are the sphere’s radius and vertical position. Since these parameters are not intuitive at first in their effect on the projection, an abstraction is provided to the user in the form of two more directly relevant controls. Their effects are illustrated in Figure 3:

- **View Distance:** Sets the distance at which the sphere intersects the ground plane. The angle of the intersection stays constant.
- **Sphere Angle:** Adjusts the angle at which the sphere intersects the ground plane, measured as the *intersection ratio* from tangential contact (0, the sphere barely touches the plane) to a dome overhead (0.5, the sphere is bisected). The view distance stays constant.

In practical terms, lowering the *View Distance* brings the ground–sphere intersection closer to the observer and produces a stronger upward lift of projected map features, which increases separation of distant candidate sources but also increases apparent geometric deformation. Increasing the *View Distance* has the opposite effect: the projected map remains closer to the terrain and appears less curved, with more features remaining at their original position.

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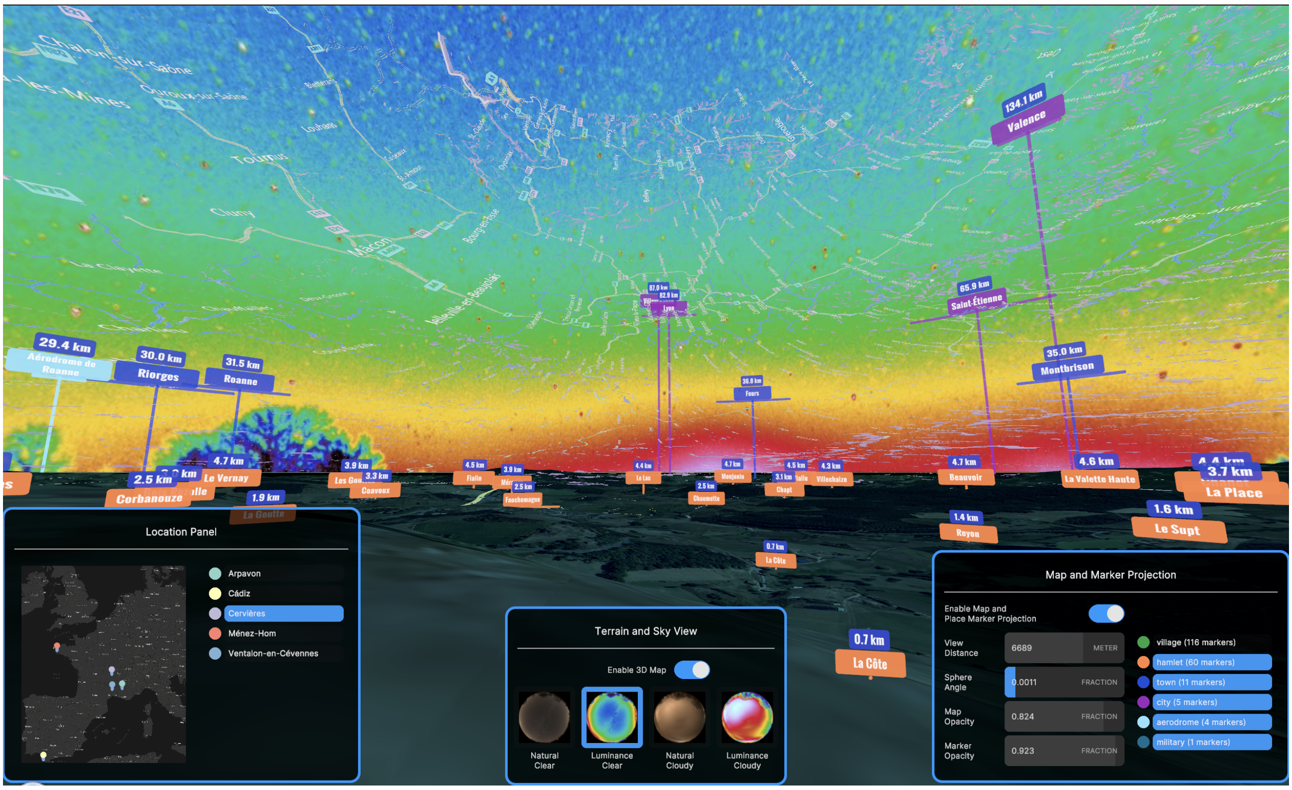

Figure 5. An immersive view with projected road map and markers, showing different types of locations in different colors.

Similarly, increasing the *Sphere Angle* (intersection ratio, toward 0.5) makes the projection more dome-like, pushing far features higher and emphasizing distances between closer features; decreasing it (toward 0) flattens the projection, preserving more of the original ground layout. This reduces vertical separation of nearby sources, but keeps far-away sources visible without needing to look up high to see them.

3.3 Cylindrical Projection

The inverse stereographic projection was specifically developed for use in immersive environments, where the large field of view and full immersion are beneficial for understanding the spatial context around a focal area (Spur et al., 2022). When this projection is viewed on a traditional flat screen with a conventional perspective camera, additional distortions from camera rotation can render the view less useful. In Figure Figure 5, the connecting lines between location markers and their origins in the landscape are perfectly vertical in world space, but appear tilted on screen. Without these connecting lines, the apparent horizontal shift of markers relative to their original position close to or behind the horizon could be misleading and might lead to misattribution of light sources to light halos. Just as we do not perceive skyscrapers to be physically slanted when looking up, this geometric behavior is not problematic in a head-tracked virtual reality context, where the projection is coupled to natural head motion (Josupeit, 2024).

Outside of VR, however, viewing the visualization on a standard monitor can be desirable: it can reduce fatigue (Biener et al., 2022), provide access to higher pixel densities, allow finer control over zooming and framing, and simplify sharing and collaborative analysis without having to set up and coordinate multiple head-mounted displays. A naive solution would be to display the same view as in the VR system and add a basic mouse-look camera, accepting the additional perspective distortions. Instead, we introduce an additional secondary projection tailored to desktop viewing and analysis: a cylindrical panoramic projection.

When the visualization is launched on desktop systems, the user can toggle between a conventional perspective view with mouse-look and zoom, or a new cylindrical projection of the same content. In the cylindrical mode, the same view consisting of the skybox (all-sky image), digital terrain, and the stereographically projected road map is rendered invisibly to the user. Instead, the rendered environment is resampled into a cylindrical image: the horizontal axis encodes azimuth, while the vertical axis encodes elevation within a configurable range, as can be seen in Figure Figure 6.

Conceptually, the cylindrical view is constructed by treating each pixel of the image as looking in a specific direction from the observer. Horizontally, the image spans a configurable azimuth range around the user (left–right), while vertically it covers a configurable band of elevation angles from below the horizon up toward the zenith. For each pixel, we determine its azimuth and elevation within these ranges and use that viewing direction to sample the underlying 3D environment (skybox, terrain, and luminous elements). The result is a cylindrical panorama in which the horizontal axis encodes azimuth and the vertical axis encodes elevation. In practice, this mapping is implemented in a single pass on the GPU, using an intermediate panoramic representation of the scene as the source for resampling.

For our use case, we restrict the vertical range to an interval from approximately -20° below the horizon to $+80^\circ$ above it. This covers the relevant portion of the sky and near-horizon environment while excluding extreme zenith and nadir directions

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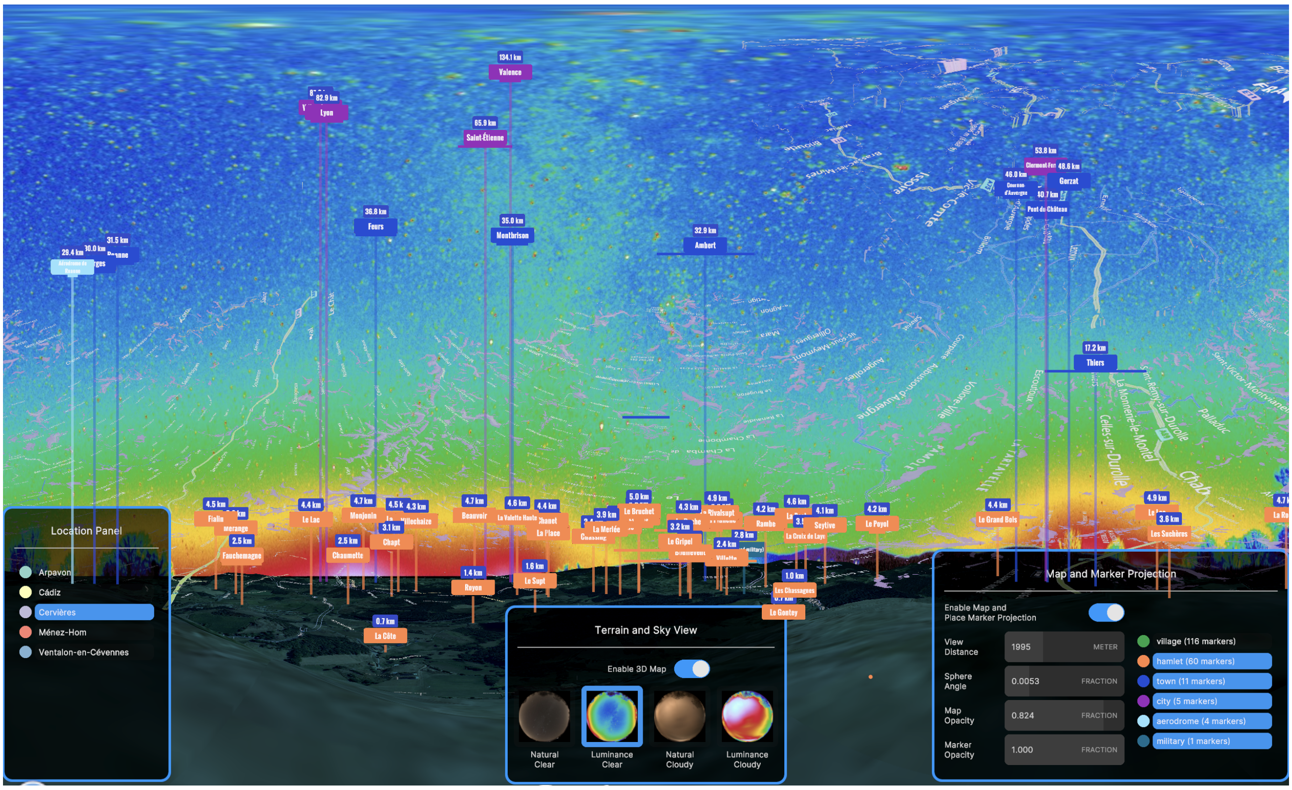

Figure 6. The cylindrical projection of the visualization system optimized for desktop use. The window can be resized, and zooming affects the horizontal compression.

where cylindrical distortions become more pronounced; however, this remains user-adjustable in the settings. The horizontal field of view Φ_h is user-adjustable by scrolling with the mouse wheel: it can be narrowed to focus on a smaller angular sector or widened toward a near-panoramic view. Crucially, because the projection is defined directly in angular space, adjusting θ_0 and Φ_h corresponds to panning and zooming the panorama without introducing additional perspective skew.

Analytical overlays such as location markers, connecting lines and arcs are not rendered as 3D geometry into the cylindrical panorama. Instead, they are generated as screen-space elements in a separate user interface layer positioned on top of the projected image. Each overlay element is associated with a world-space position and is mapped into the cylindrical coordinate system using the same angular relations as above: given a direction $\mathbf{d}$ from the observer to the point of interest, we compute (θ, φ), derive (u, v), and place a 2D icon or line segment at the corresponding position in the screen-space canvas. This decoupling ensures that symbols and text remain crisp and uniformly sized regardless of zoom level, and avoids the shape distortions that would arise if they were subject to the cylindrical resampling of the underlying image.

The resulting desktop mode therefore offers a hybrid view: the advantages that the inverse stereographic projection provides remain, and are made more legible by a subsequent cylindrical panoramic reprojection. It preserves vertical structures and supports intuitive panning and zooming, while analytic elements are rendered in a consistent angular coordinate system as high-legibility screen-space graphics. This allows users to inspect and compare halo extents, light source positions and their relationships to the terrain without the confusing perspective distortions that occur outside of an immersive VR setup.

4. Evaluation

Recent work on evaluating the perceptual fidelity of VR HMDs in reproducing spatial phenomena (Chamilothori et al., 2019, Atié et al., 2025) relied mostly on studies with non-expert participants. In contrast, for an evaluation of our tool with its analytical focus, we decided to first conduct interviews with experts. Because the Night Sky Explorer displays reconstructed and augmented visualizations rather than directly reproduced real scenes, it is essential to first confirm its efficacy and accuracy from specialist perspectives. This focus complements existing work that uses VR for designing and evaluating lighting configurations (Krupiński, 2020), and research that has examined how lighting professionals and light pollution experts perceive ALAN as an environmental concern (Schulte-Römer et al., 2019). For this reason, we conducted preliminary interviews with two experts in artificial lighting and environmental light pollution, gathering their professional feedback. This step precedes broader user-based perceptual and usability evaluations planned for future work to examine how non-expert users and stakeholders could perceive and interpret light pollution through the tool.

4.1 Method of Validation

Two semi-structured interviews were conducted with experts in light pollution analysis to collect professional feedback on the Night Sky Explorer VR application. The first expert (P1) is an engineer with expertise in environmental consulting and territorial lighting diagnostics; the second (P2) is an astrophysicist with expertise in the analysis and modeling of light pollution.

The interviews followed a semi-structured format, allowing open discussion around common themes such as current tools and methods used for light pollution visualization in their work; the added value of the Night Sky Explorer compared to existing tools; the usefulness of immersion for analysis and communication; and the main strengths, limitations, and desired improvements of the tool.

4.2 First Results

4.2.1 Understanding Light Pollution’s Origin Through Immersion Both participants felt that the immersive view makes the sources of light pollution easier to identify. P1 explained that in a VR HMD, he could immediately see which city or village was creating a specific halo, something that takes much longer to analyze on a 2D map. In addition, P1 mentioned the value of the angular extent feature, which shows how much of the horizon is affected by each light source. This information made the identification of halos much more precise. P2 imagined using this representation to raise awareness among non-experts, such as local authorities.

4.2.2 Comparison with Previous Visualization Tools Both experts reported that they currently develop and use their own analytical and visualization tools, primarily in the form of 2D cartographic representations. These maps typically encode modeled sky-brightness indicators with continuous color ramps, similar to standalone night sky light pollution maps used for diagnostics and planning (Kunz and Daab, 2024). In addition, traditional visualization methods, such as GIS-based light pollution maps or fisheye photographs, provide valuable quantitative and photographic information but limit spatial understanding of luminous phenomena. This also makes it difficult for non-specialists to intuitively understand the origin of light pollution. In contrast, the Night Sky Explorer offers an experience that immediately reveals the angular extent and spatial origin of light halos, by directly co-visualizing potential light sources with the halos. The experts emphasized that this immersive dimension represents a major advancement over conventional mapping techniques.

4.2.3 Use Cases Beyond technical analysis, participants viewed the Night Sky Explorer as a pedagogical and communicative tool, capable of translating complex scientific data into visual experiences for decision-makers, park managers, and citizens. Immersive visualization was seen as particularly relevant during the final stage of project communication, where it could illustrate different lighting and weather scenarios, such as reductions in artificial illumination or targeted dimming policies, and display their visible effects in real time.

P1 saw the Night Sky Explorer mainly as an analysis tool to identify the main sources of light pollution and to compare different areas. P2, on the other hand, imagined it as a tool to help people visualize the impact of lighting policies and discuss potential changes. He also mentioned the possibility of simulating animal vision at night to discuss biodiversity effects.

4.2.4 Limitations P2 mentioned practical constraints related to the current use of VR HMDs. The cost and complexity of deploying VR headsets still limit their widespread adoption in professional contexts. However, he considered these challenges to be temporary and technological rather than conceptual, suggesting that accessibility will improve as hardware becomes more affordable. P1 emphasized the importance of a desktop version of the Night Sky Explorer, which would facilitate communication between clients and professionals during project discussions. Both experts agreed that the VR HMD application would be particularly valuable for public demonstrations, exhibitions, or training events.

Another limitation concerns the color encoding used in luminance mode. Because we keep the legacy SQC palette for continuity with common practice, perceived differences between neighboring hues do not always reflect equal luminance steps, which can bias visual interpretation of gradient magnitude (Borland and Taylor, 2007, Crameri et al., 2020). Future versions should therefore provide an optional perceptually uniform palette while retaining the original SQC mapping for backward comparability with existing analyses.

Given that only two experts were interviewed, these results are preliminary and intended to guide further development rather than to provide statistically generalizable findings.

5. Conclusions

The Night Sky Explorer is an interactive application that combines calibrated all-sky imagery, a digital terrain model, and OpenStreetMap-derived candidate emitters within an inverse stereographic projection. By projecting road networks, settlements and other potential sources of artificial light onto a sphere surrounding the observer, and by encoding each location’s angular extent along the horizon, the system enables users to rapidly relate visible skyglow halos to plausible terrestrial emitters. The immersive VR mode leverages head-tracked navigation and depth cues to provide an intuitive focus+context view of the environment, while the cylindrical projection mode offers a complementary desktop-oriented view that preserves angular relationships and supports precise panning and zooming without additional perspective distortions.

A companion web-based tool prepares the geospatial input for this visualization by querying OSM around a chosen observation point, constructing outlines and unified footprints for relevant feature classes, and deriving angular arcs that summarize the horizontal span of each location as seen from the observer. Together, these components form a workflow that links geolocated all-sky images to a structured, analyzable representation of their surrounding emitting landscape. Preliminary expert interviews with specialists in environmental lighting and astrophysical light pollution analysis suggest that the system can dramatically reduce the time needed to identify dominant sources of skyglow, clarify the angular contribution of individual emitters, and provide a compelling medium for communicating the impacts of ALAN to stakeholders.

Beyond its immediate application to the study of ALAN, the proposed combination of inverse stereographic projection, cylindrical reprojection, and OSM-based angular extents illustrates how multi-perspective geovisualization techniques can be tailored to specific analytic tasks at the interface between remote sensing and field observations. As outlined in future work, integrating satellite-derived radiance products and simulation-based skyglow models, and complementing expert interviews with controlled user studies, will further clarify the strengths and limitations of this approach and guide its evolution as a tool for analysis, planning, and outreach.

5.1 Future Work

Aside from the semi-structured expert interviews, a formal user study could compare the VR version of the system against the naive desktop version and the cylindrical projection, as well as against the current methods practitioners use to identify sources of ALAN. Results would provide quantitative data on the system’s potential impact and guide further improvements to the user interface.

Further functional enhancements include integrating radiance maps from Visible Infrared Imaging Radiometer Suite - Day/Night Band (VIIRS-DNB) satellite data (Miller et al., 2013), in addition to or in place of the projected road maps, to introduce a more detailed view of light sources than the current location markers. A challenge here is finding a way to overlay this data with the all-sky images, as they are not discrete like roads and markers.

Recent work simulates all-sky skyglow views directly from emission maps (Dobashi et al., 2023). A system like that could be integrated with ours, allowing us to explore any point on Earth at any point in time for which there is VIIRS-DNB data, and not be limited to the manually recorded and processed photographs from a few select locations. The capabilities the inverse stereographic projection offers for navigation (Spur et al., 2022) could then be used to quickly traverse, explore, and compare different locations and conditions.

Finally, building on this, simulating or manipulating the VIIRS-DNB data itself that feeds into such a simulation would also enable urban planners and stakeholders to explore different planning scenarios, directly showing their impact on the night sky, such as shielded lighting or reduced brightness. This could identify optimal strategies for reducing light pollution, as well as raising awareness for these issues during the planning stage and beyond.

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