Towards a Mexican National Archaeological Atlas Scalable 3D Web GIS and Archival Systems for Big Data

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Abstract

The Tren Maya project, a new railway connecting major population centres and tourist sites around Mexico's Yucatan peninsula, impacted vast tracts of undeveloped land, ripe with archaeologically significant sites and landscapes. This effort necessitated the mobilization of Mexico's archaeological authorities for the evaluation of large areas with tight timelines, as well as the creation of new museums along this railway network, consolidating and cataloguing previously scattered artifact collections. Authorities invested heavily in 3D survey products to meet the rigorous requirements of the project, resulting in the creation of many 3D aerial and terrestrial LiDAR, photogrammetry, structured light datasets. These survey data offer critical insight into their subjects and have wide potential for re-use by external parties, and are of great interest to the public at large, but, their inherent complexity and density create significant barriers for accessibility. We present a scalable and future-facing web-based system and archival framework enabling the long-term accessibility, visualization, and interoperability of critical 3D data assets with existing research and site management pipelines, game/xr/metaverse environments, and machine learning training applications.

1. Introduction

In 2020 construction began on the 5-year Tren Maya project, a 1,554 kilometre railway connecting population centres and UNESCO World Heritage sites (being major tourist destinations) throughout Mexico's Yucatan Peninsula. In accordance with federally mandated regulations, and internationally recognized best practices, the Instituto Nacional de Antropología e Historia (INAH) coordinated and performed a rapid 3D digitization initiative, to acquire high resolution topographical, architectural, and artifact level imagery (LiDAR, Photogrammetry, Structured Light data) seeking to document and mitigate the impacts of hundreds of fast-paced construction projects on cultural heritage sites. These data were mobilized to inform critical decision-making through fast-paced development of new national infrastructure through a diverse set of complex uninhabited landscapes (including caves, cenotes, coastal plains, marshes, dense rainforests) much of which is rife with evidence of ancient habitation requiring further investigation (Rissolo, 2024).

The Tren Maya project also allocated funding for the development of new museum complexes at several key archaeological sites connected by the railway, planning a more permanent support infrastructure. Along with exhibit space, these planned facilities include laboratories, storehouses, visualization systems, and more. These new museums promote the centralization of important artifacts, and a comprehensive cataloguing effort, which had previously been made difficult by a wide scattering and resultant dissosciation of objects and resources related to any one site, and the temporary nature of employment for skilled technical staff.

Throughout this development, high quality 3D digital mapping products provided foundational operational references, often delivered through locally cached multi-resolution mobile GIS or web viewers. The immediate and long-term utility in both decision making for conservation and site management, research, and public engagement were made apparent to a wide range of key stakeholders, who have now organized to support an infrastructure enabling wide access to these critical datasets.

We present, in this paper, a system which catalogues and contextualizes thousands of 3D mapping products of various scales, on a global basemap. Aerial LiDAR products (Figure 1.) provide key basemaps, enabling geolocation of all other products, which are often obscured from aerial view by dense vegetation. At the feature scale, photogrammetric and mobile lidar products can be geolocated and overlaid (Figure 2.) to enable novel interactions and metric queries in real-time. At an artifact scale, structured light scans of individual objects can be digitally placed back within their original contexts (Figure 3.). As we rely on open-source web and database structures, we also have the ability to link other media, articles, reports, analyses, and custom interactive actions within geospatial annotations featuring embeddable objects (Campiani, 2023). The system enables temporal movement and overlay, including datasets depicting multi-phase excavations (Figure 4.) and day by day work progress tracking the location of individual stones through the process of reconstruction.

2. Archival Infrastructure

As of 2024, there has been no national archaeological information technology infrastructure available to catalogue, preserve, or share these important, often revelatory, data for future re-use. There have also been no overarching federal policies made regarding the restriction or sharing of the high-resolution terrain models extracted from aerial LiDAR datasets which have been a truly disruptive technology for those practicing archaeology in such densely vegetated landscape. The archaeologists are left to interpret these efforts, with some difficulty, through the lens of federal regulations passed in the 1970s, regarding the dissemination of individual photographs. Leadership within INAH has begun to investigate these issues in depth.

In collaboration with key stakeholders within INAH, academia, and non-profits engaged in digital mapping and GIS, we present a scalable and sustainable web-framework, enabling full-resolution 4D geospatial contextualization and visualization (Schütz 2016). This archaeological atlas enables effective multi-modal quick reference, in-field utility, public accessibility, and long-term re-usability of complex archaeological data assets by diverse audiences. The future-facing system architecture demonstrates and anticipates integrations within cutting edge streaming - metaverse environments and seeks to provide a holistic description of the long term academic and societal impacts of such data assets, supporting infrastructure, to federal policy makers. The system is, additionally, designed to be modular, as the nation builds its data storage infrastructure over the coming decades, while providing pathways for permanent user-facing web locations, and incentivizing collaborators to share their data by offering citable identifiers which effectively add these assets to existing academic ecosystems.

2.1 The Raw Data Archive

The foundational layer of this project is long-term archival storage for original data assets, enabling re-use by external parties. The usual progression of a survey communication, between data collectors and decision makers, necessitates the simplification of data into parcels which meet the specific needs of a given project. End-users are generally reliant on these derivative data products, which convert original data content into intermediary data products which enable greater usability but lose key attributes. As processing and visualization software evolve, we are able to re-approach legacy datasets and extract new insights from previously buried layers of information. Furthermore, we are able to open those datasets to other experts, who may possess useful capabilities and perspectives which can lend new interpretations. It is critical that these data, which are often captured at significant cost, often with public money, and often leading to significant decisions concerning the public, be open to scrutiny. We can hold these surveys and interpretations to a scientific standard, only if they are reproducible by third parties (McAvoy, 2023b).

2.1.1 Data Formats: Wherever possible we must employ open data formats which are not tied to any one software system. This can be quite challenging, as many hardware systems create black box environments, obscuring a user's access to the system's inner workings.

2.2 Metadata and Paradata

The re-use of raw data is enabled through the careful reconstruction of context. If data is to be re-used as part of a long-term monitoring effort, this context is critical. The most important questions are the simplest. Who, what, when, where, how. This simplistic approach, however, can fall drastically short of providing a clear picture of the data's quality. When was the data captured, what does it show, what doesn't it show? Which parts of the model are reliable, which are not? How much can we trust any given measurement? All too often the concepts of precision and accuracy are abstractions which must be reconstructed through narrative information. Aside from the sensor's baseline capabilities, the methodologies for grounding the sensor data in space, for aligning multiple scans together, extreme operating conditions, malfunctions, special considerations for complex materials and environments… can all contribute to deformation of a site survey (Ioaniddes, 2025). Unfortunately, many key details involved in the capture of survey data are lost, or not recorded in the first place
The records page (Mcavoy 2024)

3. Visualization and Derivatives

The mere availability of a file for download does not mean that it's accessible. Especially in this field, users are presented with significant barriers. File sizes, the availability of computer hardware, software availability… to name a few. Understanding these barriers, we strive to enable the user to visualize the data using a web environment, with free, device agnostic tools, which enable full resolution viewing of the data without download.

3.1 Streaming Architecture

To enable this kind of streaming, we build several kinds of web servers hosting tiled 3d, 2.5d and 2d derivative images. Wherever possible we prefer to employ simple Apache file servers enabling direct access to assets which are formatted for multi-resolution streaming. In some cases we use proprietary systems with built in security and scalability functions, but are always sure to provide open source alternatives.

These streamed assets must also be embeddable. By this we mean both that a viewer should be able to embed as a window in an external website (as one might have a playable youtube video inserted into a blog), and also that the data asset streams must be accessible to external viewers, where they can create additional layers of personal annotations and other data assets. For example, a 3d reconstruction project imagining the state of a building during the Maya classical period should be able to stream in a foundational 3d LiDAR data layer providing context and evidence for the decisions being made in the reconstruction.

3.1.1 3D Data Products: AS our primary 3d viewer, we employ the Potree point cloud system (Schutz, 2016) built upon the Three.js WebGL game engine, and a number of customized templates, to enable the placement and contextualization of different data types in the same environment (Campiani, 2023). While the Three.js viewer supports over 40 different types of 3D formats, including many varieties of meshes, voxels, and points, few of these particular formats are optimized for large scale formats, enabling compressed stream-able parcels. We have found this system to be more performant than the mesh systems we've tried, including Cesium tiles (Cesium, 2025) and 3Dhop's Nexus (Potenziani 2015) loader (Potenziani, 2015). For this reason, we often convert non-point objects like rasters and meshes into point clouds, by sampling points at pixel and texel levels. We've also found that the system works well with volumetric data (Rubio 2021), enabling the placement of voxel based computed tomography (CT), scanning electron cryomicroscopy (CryoSEM) magnetic resonance imaging (MRI), and ground-penetrating radar (GPR) data.

Aside from the optimized streaming capabilities Point clouds offer a number of advantages when communicating sensor data.

Points are the native format for LiDAR products. The data structure is essentially the same as a simple spreadsheet, where each point is represented as an XYZ coordinate, with an unlimited number of additional descriptors tied to them. They can support a wide range of additional data attributes inherent to the modality. Attributes like: intensity (reflectance), gps time, source, distance from point of acquisition… and also derivative attributes like classifications, segmentations, and other annotations. Potree is built around the aerial LiDAR focused LAS point cloud file format (ASPRS, 2019), which is then converted into a compressed octree structure. The viewer will also support the viewing of cloud optimized point cloud (COPC) files in a LAS/LAZ (Manning, 2016) wrapper, but these are not as performant or aesthetically pleasing within the current implementation of Potree, (Schutz, 2023).

The Potree assets are layered on top of a 3d global basemap provided through Cesium.js (Cesium, 2024) . The resolution of the elevation layer is 30 meters within the country of Mexico. Users are presented with options to switch between several free imagery layers, including OpenStreetmaps and Bing imagery. These layers provide important context with labels for roads, towns, and archaeological features baked in. The basemap is currently limited in its support for coordinate systems. lat/long projections are not supported, so we are limited to using meters-based projections with regional constraints. In this way, it is currently impossible to add data from Mexico City (UTM 14N) and Yucatan (UTM 15N/16N) within the same viewer without causing significant distortion to one of the two sites. Cesium.js is also limited by its reliance on the WGS84 vertical datum. Many survey grade datasets use more accurate vertical datums, and the result is a noticeable gap between the dataset and the basemap below, often as much as 50 meters. These issues can be better addressed through the Cesium Ion implementations in Unreal Engine, but this implementation fails to meet our needs regarding performance, accessibility, and scalability. Ideally, we would like to host additional tile sets which will feed into the variety of Cesium Ion visualization environments, and we are keeping a close eye on the continued development of this platform.

The web environment allows us to build upon highly extensible simple, and well documented, features, enabling streamlined interactions through space and time. We present, below, 4 examples modelling key interactions and capabilities we expect from our data, communicating the scope and utility of these interactions.

1) Layer validation and reference. Switching between raw and interpolated aerial LiDAR data products. We can see the classified point cloud of Palenque’s monumental centre with vegetation enabled, and then switch seamlessly to the interpolated and hill shaded product which better communicates subtle topographical features. As the derivative product fills in gaps, we may need to refer back to raw data to reference anomalies, and validate findings (figure 1).

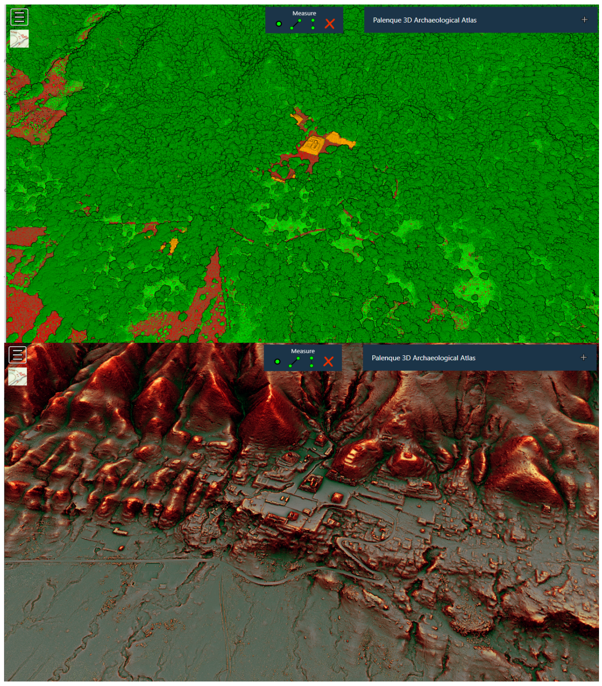

Figure 1. Classified LiDAR (above) and derived digital surface map (below) of Maya site of Palenque (Campiani, 2023)

2) Multi-modal fusion. It is very useful to overlay multiple models from differing sources at the same time. Here we see a fusion of a drone based photogrammetric scan of the Osario pyramid at Chichen Itza (McAvoy, 2023a) with a SLAM LiDAR model of the interior shaft and cave beneath the structure. Within the Potree system we can align one to the other and create a cross-section, giving a full view of the context (figure 2).

3)

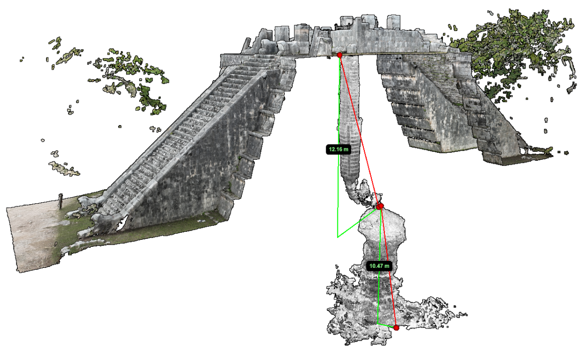

Figure 2. Cross section of the Osario pyramid at Chichen Itza, combining aerial photogrammetry with mobile LiDAR

4) Contextualization of museum pieces. As objects are moved out of their original contexts, into museum collections or store houses, it becomes necessary to digitally place them back in their previous positions. In this example we see a carved piece of the door jamb in Chichen Itza’s upper temple of the Jaguar, previously housed in the Gran Museo Mundo Maya some 124km away in Merida (figure 3).

Figure 3. Door jam in temple of the Jaguars at Chichen Itza (left) and again with museum housed panel digitally recontextualized

5) Excavation time series overlay. Excavations are destructive in nature and must be carefully documented to spatially contextualize all artifacts found within. Here we see 8 phases of excavation within the Palenque J7 temple complex, starting from the contemporary surface, down 5.44 meters to a burial beneath the platform structure (figure 4).

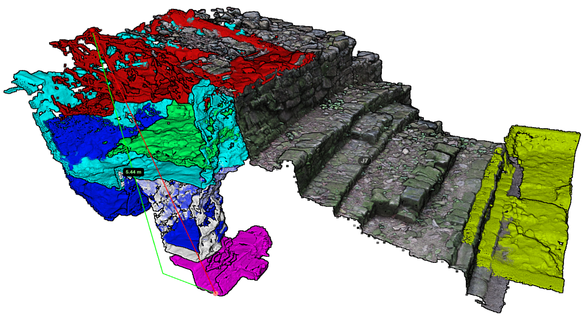

Figure 4. Time series showing 8 excavation layers at J7 complex, Palenque

6) Reconstruction documentation. Many monumental structures are reconstructed from piles of loose stone. The skillful process by which these stones are analyzed and re-assembled is often opaque and rarely documented. Here we can see, very clearly, the movement of each stone and their labelling scheme in the re-assembly of Chichen Itza’s 3C11 Temple 6 in 18 phases (figure 5)

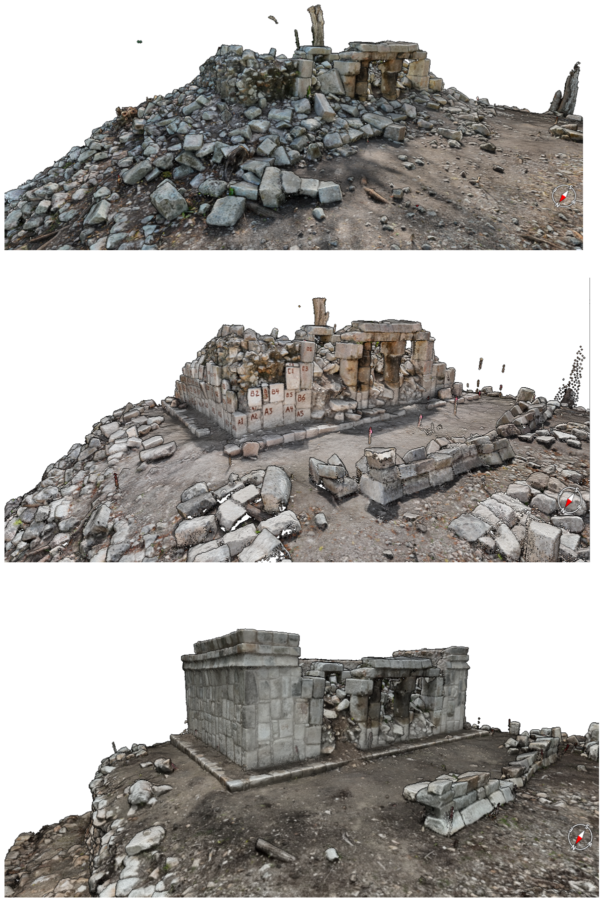

Figure 5. Temple 6, 3C11, at Chichen Ita, phases 0 (top) 5 (middle) and 17 (bottom).

3.1.2 Geographic Information Systems: Though 3D products provide a means for full-resolution visualization and data validation, they fall short in many ways. It is rare to find researchers or heritage site managers relying entirely on 3D models, as the underlying software does not currently support a comprehensive suite of analytics and management tools. In most cases this kind of work is performed within a geographic information system (GIS). The majority of stakeholders within the INAH archaeological community have traditionally employed the QGIS open source tool (QGIS, 2025), which offers a wide range of features, and integrates with many other open source toolsets. With the advent of the Tren Maya project came an increased adoption of the proprietary ESRI ArcGIS suite, offering many of the capabilities with a greater emphasis on enterprise support for large organizations and government.

The Centro Investigador del Sistema Acuífero de Quintana Roo (CINDAQ) and their SmartCave system (Figure 6) provides a key example for a functional mapping and asset navigation system for some of the worlds most complex and extensive cave systems. Though built around caves and aquifers in the Yucatan Peninsula, its functionality and methodologies are exemplary for terrestrial and built-environment settings. The system combines traditional professional cave survey methodologies with dynamic images services and occasionally linking out to 3D derivative products (Brandi 2020). INAH has come to rely on this system, operationally, and there is interest in extending the webGIS functionality they’ve built in partnership with and EarthAnalytic and ESRI’s ARCGIS online platform

Figure 6. CINDAQ SmartCave Manager system built on ESRI ARCGIS Online (Devos, 2024)

One of the key advantages of this approach is optimization and cloud-based scalability of web-based visualizations for streaming. It is common to explore the same digital elevation maps (DEMs) in a variety of hill shades. Through the ARCGIS image server, DEMs can be rendered dynamically on the client side to produce custom hill shades more suitable for archaeological investigation. s, by hosting the baseline data one, instead of as 10 different imagery products, the archive is significantly streamlined.

3.2 Media and Annotations

Web based systems offer a wide array of integrations with traditional media (video, sound, images…) and textual annotations. There is great potential to relate data to crowdsourced annotation within a geospatial context, as is demonstrated by the wiki data integration with OpenStreetMap (Wiki data, 2025). The annotations themselves, attaching media assets and text to a coordinate, can be served within a simple database which integrates across a wide range of 3D and 2D data map views. It is ideal that the individuals involved in data acquisition provide contextual annotations regarding the nature of their work. Anomalies, errors, environmental challenges… can be shared in this way and should be curated within the archive. These annotations can currently be saved in a simple text file, and ingested into a database, but we have yet to design an interface which simplifies this linking between objects.

External annotators, which might include academic research or virtual tours, should be maintained by their creators outside of the atlas. These users can stream the data assets into whatever environment they prefer, layering their personal notes on top of the shared asset. Examples of this functionality must be curated within the atlas's documentation.

3.3 Metaverse, VR, XR

The larger vision of this project, as demonstrated by the examples in section 3.1.1, is to provide a framework linking media, annotations, and other digital objects spatially and temporarily. These are the baseline capabilities for an immersive metaverse environment, where users can explore the archive as they might explore the real world, navigating through spaces and handling artifacts at a one-to-one scale. As we've demonstrated, the technical framework for this is in place. The Potree and Three.js environment does support VR and XR natively, though the implementation is currently unintuitive and buggy. It is our hope that, by providing a sandbox of ready-to-use data assets with mapped relationships, we will promote development of further integrations on this front.

4. Data Access and Publication

All archaeological research in Mexico requires a permit from the National Institute of Anthropology and History (INAH). Both national and international PIs must submit a proposal to the Archaeology Council of INAH for review. Research activities (proposed and conducted) must comply with the Federal Law Pertaining to Archaeological, Artistic, and Historical Monuments and Zones and the Standards for Archaeological Research in Mexico (and the Regulations therein). Foreign nationals and Mexican investigators alike are held to the same professional standards and assume the same research and reporting responsibilities under the law.

Technical reports (informes) must be submitted to INAH after each field campaign. However, these documents are not made available to the public and essentially can only be shared at the PI's discretion. The result is that research outputs – including 3D data – are often sequestered until they are published. It is not uncommon for data to go unpublished (or otherwise un-disseminated) for years. This applies not only to survey or 3D data, but more commonly to excavated materials, such as ceramics and lithics. While complying with the letter of the law (and fulfilling the PIs contractual reporting obligation), this somewhat common practice effectively does the community a disservice by "locking up" data that could be of benefit or interest to other scholars, educators, or the general public.

We would endorse an arrangement where the PI is required or obligated to publish (online) a citable "work in progress" which would not only provide an overview of the research results – and, ideally, a publicly available subset of the data – but also make clear to the reader the PI's future publication priorities, plans, or commitments. "Hoarding" data is more often attributed to the PI's fear of having their original data prematurely analyzed, interpreted, and published by others. Interestingly, there are often uses or applications of the data that fall outside of the PI's expertise or interest and would otherwise not be pursued.

If a structural engineer, for example, scans a temple for the purpose of conducting a comparative study of specific architectural elements, they may be unaware of the value of those data to an art historian who is researching murals. Somewhat ironically, by sequestering data, the PI might be denied the opportunity to benefit from an unanticipated publication led by a new colleague. By making one's research intentions known via a short post-campaign online publication, such opportunities for mutually beneficial collaboration can be explored.

This project represents an effort to separate data publication from the publication of interpretive scholarship. Within the current academic system, the two are entwined. When data is published, it is only done so in service to academic works. We hope to provide a public-facing framework which properly acknowledges the individuals involved in the creation of key data assets, allowing non-academic collaborators to become participants in the academic discourse around their work, and to ensure that the correct contacts are provided to answer critical questions as these data are re-used in external contexts. Simultaneously, there must be a way to foster healthy criticism regarding these data products, especially as the availability of certain data may be used as a justification to approve or deny additional data acquisition campaigns. If a work or an interpretation is problematic, there must be a reference and means for the community to engage in discussion.

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4.1 Digital Object Identifiers (DOI)

Cataloguing projects, especially in Mexico, have historically been plagued by unstable information systems infrastructure. It has not been uncommon to find physical artifacts with two or three different catalogue numbers written on the piece, sometimes still without readily available reference for any of those numbers. The same issue exists in the digital world, as websites and digital catalogue projects are funded, then go defunct. Their trails, still evidenced by external sites, lead to dead ends. Digital object identifiers (DOIs) are a means to combat this issue and prepare for the eventual migration of assets between systems as supporting human and technical infrastructures shifts. The DOI is an additional layer of identification registered with a third party, which functions as a sort of forwarding url. By always referencing that forwarding URL, we can change the address and project of the object programmatically without worrying about breaking its links to the rest of the web. The DOI is widely adopted by top scholarly publishers and offers, along with long term security, a gateway into the realm of academic discourse, as any object with a DOI can be harvested automatically by scholarly aggregators and officially linked to its creators.

4.2 Incentive Structures

One of the key metadata requirements to enable effective re-use of complex data is authorship. Identifying individuals involved with the acquisition. We cannot possibly account for the endless complexity of possible re-use cases, it is critical that users are able to contact expert stakeholders for questions about their data products. We need to incentivize these experts to participate within this system, and this can be a difficult task.
This project requires the direct participation of a diverse range of highly skilled and active stakeholders, often working long hours in difficult conditions, with limited access to technology. Data preparation and annotation can be a tedious task, and in the face of competing priorities, it is difficult to find time for this work when there is no immediate and specific need for a product. It is therefore critical that we create adequate incentives to motivate stakeholders to share their data. Part of this incentive structure is the utility of our automated visualization systems, offering users increased access to their products beyond the capabilities of their own personal computing environment. The other incentive structure we employ is around providing proper recognition for individual efforts. Data acquisition campaigns are logistically complex, involving many collaborators and experts across multiple fields.
DOI systems

4.3 Security Concerns

The ancient heritage of Mexico covers a vast and varied landscape which cannot possibly be policed and protected. By making certain location information available, we put sites at risk of looting and destruction. It is therefore a priority to protect these sites, ensuring that certain imagery and coordinates which would put the sites at risk are restricted, while still maintaining spatial relationships between objects. This can be accomplished through random geographic offsets, or local coordinate systems, but the effectiveness of this strategy may vary by location, as users may cross reference publicly available imagery products. Subterranean and sub-canopy features may be protected from this threat for the time being, but the changing nature of the landscape and the availability of additional references in the future present concerns.

5. Discussion

We present this framework, communicating both exciting possibilities for the access, maintenance, and study of important global heritage sites, but also to try to show the technology trends which policy makers must expect to contend within the near future. Many of the laws regarding the sharing of cultural heritage in Mexico are based upon laws passed in 1972 regarding the dissemination of photographs. Cultural heritage professionals are left to interpret all current efforts based on these older regulations. One example is a lack of clarity regarding 3D models. One could argue, in interpreting these regulations, that any 3D asset could be viewed and used without restriction, unless an individual were to take a screenshot of that object, only then would the laws apply in restricting its dissemination.

In 2023 and 2024 the authors of this paper had presented these concepts for access and visualization to the general council for archaeology (Consejo de Arqueología) of INAH charged with authorization of archaeological projects, the protection of archaeological sites and artifacts, and the promotion of public awareness about archaeology.

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