topo4d: Topographic 4D STAC Extension for Curating and Cataloging Multi-Source Geospatial Time Series Datasets

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Abstract

Spatiotemporal analysis of geospatial time series data has gained increasing attention with the emergence of 4D point clouds and automatic acquisition technologies such as permanent laser scanning (PLS), time-lapse photogrammetry, and uncrewed aerial vehicle (UAV) platforms, enabling near-continuous monitoring of Earth surface dynamics for change detection and process characterization. However, facing massive data volumes through the temporal domain, current topographic data curation practices often rely on empirically determined data processing and management, which may significantly affect reusability, interoperability, and hence processing efficiency due to the absence or heterogeneous nature of metadata. The need for standardized approaches to manage time-dependent metadata has become critical as the demands for sharing data and reproducing analysis across tools and application domains increase. We propose a topographic 4D extension (topo4d) to the SpatioTemporal Asset Catalog (STAC) framework, which provides an open and extensible specification for automatic metadata curation and FAIR data management practices. This paper demonstrates how the topo4d extension facilitates the interoperability and reusability of 4D datasets and presents the corresponding metadata curation workflows applied to two real-world environmental monitoring applications.

1. Introduction

The rapid growth of high-frequency Earth observation, ranging from multi-temporal to time series and near-continuous (so-called 4D) acquisitions, acquired from satellites, airplanes or uncrewed aerial vehicles (UAVs), and ground-based platforms, has created great opportunities for monitoring Earth surface dynamics caused by environmental processes or anthropogenic activity. These observations include point clouds (e.g., from photogrammetry or LiDAR), imagery (e.g., optical or radar), and end products (e.g., terrain models, orthomosaic images, or change maps). However, the complexity and diversity of these data often create barriers between data providers, curators, and users to interact effectively. This becomes especially pronounced in handling and analyzing dense topographic time series, as acquired, for example, through permanent laser scanning (PLS) (Lindenbergh et al., 2025) or time-lapse photogrammetry (Eltner et al., 2017). In particular, the lack of standards for time-dependent metadata, formats, and interfaces poses challenges to the *Interoperability* and *Reusability* as central components of FAIR principles (Wilkinson et al., 2016).

The geospatial community increasingly publishes open 4D datasets with comprehensive metadata, but heterogeneous practices across repositories still complicate access and reuse for users. Metadata for 4D datasets are often scattered in file headers (e.g., LAS/LAZ files; ASPRS, 2019), processing reports, or customized formats, often requiring tailored approaches to compile data for own workflows. This heterogeneity becomes evident when examining recently published open-access topographic 4D datasets, such as Kijkduin (Vos et al., 2022), Noordwijk (Vos et al., 2023), Helheim Glacier (Shahin et al., 2025), and Schneeferner (Anders et al., 2023). Most follow a similar strategy: common metadata are listed on the repository website (e.g., PANGAEA[1], Zenodo[2], or institutional repositories), and acquisition settings and processing details are distributed as auxiliary files in PDF or TXT format. Time-dependent metadata are typically stored alongside each epoch as separate files, and data assets are available as compressed ZIP files. Although file previews are available, metadata remain fragmented and lack interoperability for different tools from the perspective of diverse user groups. Encouragingly, some datasets demonstrate a more integrated approach. LiPheStream (Wittke et al., 2024) utilizes a GeoJSON-based design to present an interoperable catalog containing the metadata fields and individual tree properties, in addition to hosting the data along with metadata and auxiliary files (e.g., digital terrain models, tree attributes, and tree maps). This catalog can be imported, for example, into the pytreedb database, allowing efficient querying, management of individual trees across space and time before downloading the actual dataset (Höfle et al., 2023). Such catalog-based designs illustrate how standardized, machine-readable metadata could enable efficient querying and sharing across repositories.

Beyond repository-level heterogeneity, metadata fragmentation also occurs within point cloud processing tools. Most software primarily focus on processing and managing only specific parts of metadata relevant to their respective processing steps, without offering a holistic framework for multi-source integration (e.g., imagery and text). Although each tool adheres to existent standards and follows established best practices within its own ecosystem, interoperability between them remains challenging. For example, laspy[3] supports standard LAS headers and point attributes, with extensibility through Variable Length Re-

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[1] `https://www.pangaea.de/`
[2] `https://zenodo.org/`
[3] `https://github.com/laspy/laspy`

https://doi.org/10.5194/isprs-annals-XI-2-2026-545-2026

cords (VLRs) (ASPRS, 2019). Open3D focuses on geometry and visualization with minimal metadata support (Zhou et al., 2018). PDAL stores metadata within its processing pipeline using a JSON tree structure, allowing customized metadata storage as the ”MetadataNode” object (Butler et al., 2021). pointcloudset enables the analysis of large point clouds over time by its custom *Dataset* Class, which embeds a timestamp list and a dictionary that supports basic metadata (original files, topic), but more detailed metadata have to be added manually (Goelles et al., 2021). Similarly, py4dgeo introduces temporal awareness for cross-time analysis, including timestamp information and transformation matrices per epoch during analysis pipelines, but relies on metadata management mostly outside the software framework (Anders et al., 2026). CloudCompare[4] enables comprehensive interactive point cloud processing, but requires storing metadata separately (e.g., the transformation matrix or change analysis parameters). These tool-specific practices vary in how they handle metadata throughout the data lifecycle (Table 1) and lack bridging. Therefore, standardized metadata that are interoperable with, yet independent of specific processing tools are essential to enhance the efficiency and long-term reusability of topographic 4D datasets.

To address reusability and interoperability challenges, the geospatial community has developed standardized metadata frameworks such as ISO 19115 (Kresse and Fadaie, 2004), the Open Geospatial Consortium (OGC) standards (Kamel Boulos et al., 2011), and the SpatioTemporal Asset Catalog (STAC) specification (Radiant Earth Foundation, 2018). Therein, STAC provides a lightweight, JSON-based structure for describing and cataloging spatiotemporal assets, with native support for extensions that adapt the schema to various use cases, including specific data types (e.g., point clouds, radar and optical imagery, raster products, climate variables), additional metadata (e.g., scientific references, satellite parameters), or supplementary assets (e.g., precomputed bands, human annotations, features of interest) (Charette-Migneault et al., 2024). Its flexible, machine-readable format makes STAC particularly suited for harmonizing multi-source 4D datasets.

However, existing common metadata fields and extensions of STAC do not yet explicitly support complex time-dependent relationships between epochs for 4D monitoring. Each point cloud epoch represents one acquisition in time, contributing to extensive 4D data archives that require consistent metadata management. Without systematic handling, parameters such as transformation matrices used in alignment (e.g., via Iterative Closest Point, ICP (Besl and McKay, 1992)) may be lost or inconsistently applied during long-term change analysis. To address these limitations, our work proposes the *topo4d* STAC extension, an interoperable metadata schema for curating and cataloging growing multi-source topographic 4D datasets. The main contributions of this paper include:

- Defining five major metadata categories and corresponding fields for topographic 4D datasets to guide metadata collection throughout the data lifecycle.
- Proposing the topo4d STAC extension specification as a foundation for managing metadata of topographic 4D datasets, emphasizing the importance of metadata across the temporal dimension.
- Presenting a systematic curation workflow for harvesting, transforming, and utilizing metadata from topographic 4D datasets to create curated catalogs for two real-world natural scenes for environmental monitoring applications.

2. Metadata Categories and topo4d STAC Extension

2.1 Metadata Categories and Fields

Existent work has emphasized that metadata should include common elements with domain-specific details (Kim, 1999; Brodeur et al., 2019). We summarize appropriate metadata fields and semantics needed to represent topographic 4D data, aiming to extend the core STAC specification for dynamic Earth surface datasets. This section defines five categories: Common, Acquisition, Processing, Time-dependent, and Assets (Fig. 1).

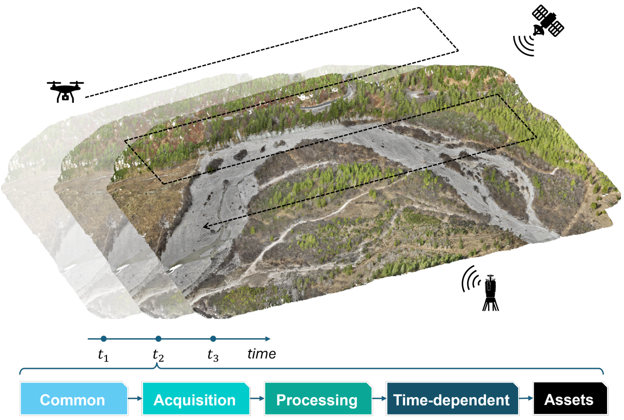

Figure 1. Different metadata categories (Common - Acquisition - Processing - Time-dependent - Assets) generated during typical topographic spatiotemporal data curation pipelines.

Common metadata. Basic information of a dataset, regardless of disciplines, serves as the core component of the metadata and the identification of the data. It includes descriptive information (e.g., title, description, abstract), administrative information (e.g., license, providers, owners), and technical metadata (e.g., instrument and platform used in data collection). The common metadata is typically recorded at the start of the campaign and remains consistent until the dataset is published.

Acquisition metadata. Details of planning and execution of a data collection campaign. It documents parameters from the planning phase (e.g., acquisition mode), the execution phase (e.g., duration, view orientation), and the evaluation phase (e.g., positional accuracy). The specific fields vary depending on the observation technique, i.e., passive or active sensing, and the types of instruments, i.e., satellite, airborne, or ground-based systems. Importantly, the acquisition metadata is finalized and remains fixed once the acquisition is complete.

Processing metadata. Parameters applied, generated, or reused during the data processing. It reduces barriers for users by improving interpretation (e.g., data type), reproduction (e.g., resolution, product information), and dissemination (e.g., georeferencing), and it assists curators in tracking processing workflows. Method-specific parameters are wrapped as the product information to allow customization when applying different processing workflows. The processing metadata may differ across product levels and processing settings, even when derived from the same raw data source.

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[4] `https://cloudcompare.org/`

Metadata Catagory	Field	laspy	Open3D	PDAL	pointcloudset	py4dgeo	CloudCompare	STAC (topo4d)
Common	Basics	✓	✗	✓	P	✗	✓	✓
	Instrument	P	✗	P	✗	✗	✗	✓
	Platform	P	✗	P	✗	✗	✗	✓
	Licensing	P	✗	P	✗	✗	✗	✓
	Provider	P	✗	P	✗	✗	✗	✓
Acquisition	Acquisition mode	P	✗	P	✗	P	✗	✓
	Measurement duration	P	✗	P	✗	P	✗	✓
	View orientation	P	✗	P	✗	P	✗	✓
	Positional accuracy	P	✗	P	✗	P	✗	✓
Processing	Data type	✓	✓	✓	✓	✓	✓	✓
	Spatial resolution	P	✗	P	✗	✗	✗	✓
	Georeferencing	✓	✗	✓	✗	✗	P	✓
	Product information	P	✗	P	✗	✗	✗	✓
Time-dependent	Datetime	P	✗	P	✓	✓	P	✓
	Timezone	✗	✗	✗	✗	✗	✗	✓
	Alignment	P	✗	✓	✗	✓	✗	✓
	Publication tracking	P	✗	✗	✗	✗	✗	✓
Assets	Media type	P	✗	P	P	✗	✗	✓
	Image data	✗	✗	✗	✗	✗	✗	✓
	Point cloud data	✓	✓	✓	✓	✓	✓	✓
	Supplementary data	P	✗	P	✗	✗	P	✓

Table 1. Comparison of metadata type support across common 3D/4D processing tools, with the last column showing the fields supported by STAC and our proposed extension topo4d (orange check mark). A check mark indicates that a tool supports the metadata type, a cross mark means lack of support, and P indicates partial support requiring customized definitions. The fields are organized into five categories, which represent key stages of metadata creation shown in Fig. 1.

Time-dependent metadata. Metadata vary across datasets acquired at different timestamps (epochs) and maintain the connections between multi-temporal observations of the same scene. It supports change analysis by providing alignment information (e.g., transformation matrix, reference epoch) between epochs and allows archived data from different sources to be integrated. In addition, it extends spatial search into spatiotemporal search. The metadata is typically tied to the initial timestamp of the data collection.

Assets metadata. Direct entry about the actual data. It documents the format (e.g., media type) and storage location of the dataset. Format include an image, point cloud, document, or any other type. Data can be hosted in the cloud, stored locally, or centralized on High-performance computing (HPC) systems, as long as it is accessible through the given address. Assets metadata serves as the direct and final link to the data itself.

2.2 STAC Extension for Topographic 4D Datasets

The STAC specification defines a standardized framework for describing and cataloging spatiotemporal assets that capture information about the Earth within a certain range of spatial and temporal scales (Radiant Earth Foundation, 2018). Building on STAC’s native support for extensions, our proposed topo4d extension[5] introduces fields to represent time-dependent metadata in topographic time series datasets. It defines a JSON schema that captures the essential metadata for 4D topographic observations. This schema extends the STAC standard by incorporating attributes such as acquisition settings, processing parameters, uncertainty metrics, and alignment transformations, ensuring interoperability with other STAC-compliant ecosystems, i.e., established STAC extensions[6]. Particularly, the topo4d extension ensures that time-dependent metadata are not treated as temporary annotations but as first-class, schema-defined fields. This structured metadata enables automatic validation and improves queryability.

Existing 4D topographic observation metadata can be mapped to topo4d-specific fields in a catalog according to the extension schema (Table 2). In particular, two essential object fields *topo4d:trafometa* and *topo4d:productmeta* are defined:

- *topo4d:trafometa* contains multi-epoch alignment metadata, including co-registration transformation, registration error, and reference epoch, e.g., parameters computed by ICP or its variants (Besl and McKay, 1992; Yang and Holst, 2025).
- *topo4d:productmeta* describes processing-related information, such as product type, algorithm parameters, data source, and product level. It is primarily used when the asset represents a derived product, such as a digital elevation model, orthomosaic image, mesh, quantitative change information or other thematic outputs.

We reviewed the metadata handling capabilities of popular open-source point cloud processing software, alongside the corresponding metadata fields supported natively by STAC and with our topo4d extension (Table 1). The proposed topo4d extension provides a comprehensive metadata schema specifying all relevant fields accessible to different tools and processing steps, thereby ensuring interoperability and completeness in managing multi-source topographic 4D datasets across tools and pipelines.

3. Metadata Curation Workflow with topo4d STAC

This section presents a systematic approach to harvesting, transforming, and using metadata from 4D topographic datasets. We define a dataset as $\mathbb{D} = (M, D)$, where M refers to the metadata describing the data assets $D = \{d_1, d_2, \ldots, d_n\}$, and each d represents an individual data asset, such as an image or point cloud. The objective is to transform unstructured or heterogeneous metadata into an interoperable form M^*, resulting in a curated dataset $\mathbb{D}^* = (M^*, D)$ that complies with our topo4d STAC extension.

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[5] `https://github.com/tum-rsa/topo4d`

[6] `https://stac-extensions.github.io/`

Field Name	Type	Description
topo4d:data_type	String	The type of data: pointcloud, mesh, raster, vector, text
topo4d:timezone	String	Timezone of the acquired date, e.g., ”UTC+1”, ”Europe/Munich”
topo4d:acquisition_mode	String	Acquisition method, such as ”ULS”, ”UPH”, ”TLS”
topo4d:duration	Number	Time duration of the measurement in seconds
topo4d:spatial_resolution	Number	Spatial resolution in meters (sampling interval or grid spacing)
topo4d:positional_accuracy	Number	System measurement error or sensor accuracy in meters
topo4d:orientation	String	Survey pattern: ”Nadir”, ”Oblique”, ”Nadir+Oblique”
topo4d:global_trafo	Array	4x4 transformation matrix for 3D point cloud georeferencing
topo4d:trafometa	Object	Metadata for inter-epoch transformations and co-registration
topo4d:productmeta	Object	Metadata for derived products including processing parameters

Table 2. Metadata properties proposed by topo4d extension.

3.1 Metadata Harvesting

Metadata harvesting is the first step towards harmonizing diverse metadata sources. These may include metadata stored in public repositories (e.g., PANGAEA, Zenodo), centralized servers (e.g., HPC storage), or local devices. Additionally, information embedded directly within the data files themselves (e.g., headers of LAS/LAZ), can be parsed to extract technical parameters such as acquisition settings or processing details.

We define two major sources for harvesting: (1) raw or external metadata M_0, which includes descriptive information such as common, acquisition, processing, and assets metadata; and (2) data-embedded metadata M_d, which primarily includes acquisition and processing information extracted from the internal file structure of the assets. The final harvested metadata is expressed as the union of both structured components:

$$M_{dict} = M_0 \cup M_d \tag{1}$$

where $M_{dict} = \{(k_i, v_i)\}_{i=1}^{m}$ represents a harmonized key-value dictionary containing all m metadata elements.

During harvesting, existing metadata and additional descriptors (e.g., implicit metadata from data assets) are standardized into a uniform format, shown as ”Metadata Layer” in Fig. 2. This unified M_{dict} (e.g., a CSV table or a JSON file) ensures that subsequent curation functions can operate automatically and consistently, regardless of the original data source or format.

3.2 Metadata Transformation

We transform the unified M_{dict} into curated metadata M^*, which are organized according to the STAC and topo4d extension. The STAC framework defines a JSON-based schema S_{stac} for structuring metadata at different hierarchical levels, and the topo4d extension provides an extended schema S_{topo4d} for describing the domain-specific metadata of topographic 4D datasets in a unified way.

$$M^* = \phi(M_{dict}, S) = (G, C, I) \tag{2}$$

Here, ϕ is the curation function that structures the metadata dictionary M_{dict} following the STAC schema S, which includes the basic schema S_{stac} and additional extensions such as S_{topo4d}. The curated metadata M^* consists of individual items I, collections of items C, and a catalog G that organizes these elements hierarchically under the STAC framework.

Creation of individual items. Each STAC item I_i corresponds to one observation of the scene (i.e., an individual epoch). In this step, we transform the harmonized metadata M_{dict} into item-level metadata according to the STAC schema S, which can be adapted to include different extensions (e.g., projection[7], point cloud[8]) based on application demands. Each item I_i contains standard GeoJSON fields (e.g., *id*, *type*, *geometry*, *bbox*, *properties*) as well as additional informational fields (e.g., *stac_version*, *links*, *assets*, *stac_extensions*, and optionally *collection*) describing the assets (Radiant Earth Foundation, 2018).

Each field contains specific information to make the item both human- and machine-interpretable. For example, *id* identifies the unique observation, *geometry* and *bbox* provide spatial extent, *properties* store more detailed metadata, including acquisition, processing, and time-dependent variables. The *links* connect the item to the other STAC entities, while *assets* reference to the actual data files through either an absolute or relative path. Finally, *stac_version* and *stac_extensions* specify the schema that constrains and validates all fields. Through this structure, each STAC item I_i provides a complete, self-contained description of one epoch in the topographic 4D dataset, combining common, acquisition, processing, time-dependent, assets metadata in a standardized format that supports efficient spatial and temporal querying.

Assembling items as a collection. Once individual items I_i have been created, they can be grouped into a STAC collection C representing a coherent topographic 4D dataset or monitoring campaign. A collection aggregates a set of items sharing common spatial coverage, acquisition setting, or research interest: $C \leftarrow \{I_i\}_{i=1}^{n}$, where n is the number of items within this collection. A STAC collection builds upon the STAC catalog by including additional metadata describing the grouped items. These additional fields to describe a collection include spatial and temporal *extent* of the data, *license*, *keywords*, *providers*, *summaries* (Radiant Earth Foundation, 2018).

The collection structure enables semantic organization and efficient querying. Users can search by spatial extent or temporal range, sensor and/or platform in case of multi-source data, or processing level at the collection level without inspecting each item individually. Each collection can further include references to derived products, such as terrain models or change layers, and may be linked hierarchically to higher-level catalogs. In this way, C serves as the major organizational unit connecting individual STAC items into a logically and semantically consistent topographic 4D dataset.

Creating a catalog. A STAC catalog G is the highest unit in the architecture, which provides a top-level structure for navigating and managing metadata. It typically contains general

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[7] `https://stac-extensions.github.io/projection/v2.0.0/schema.json`

[8] `https://stac-extensions.github.io/pointcloud/v2.0.0/schema.json`

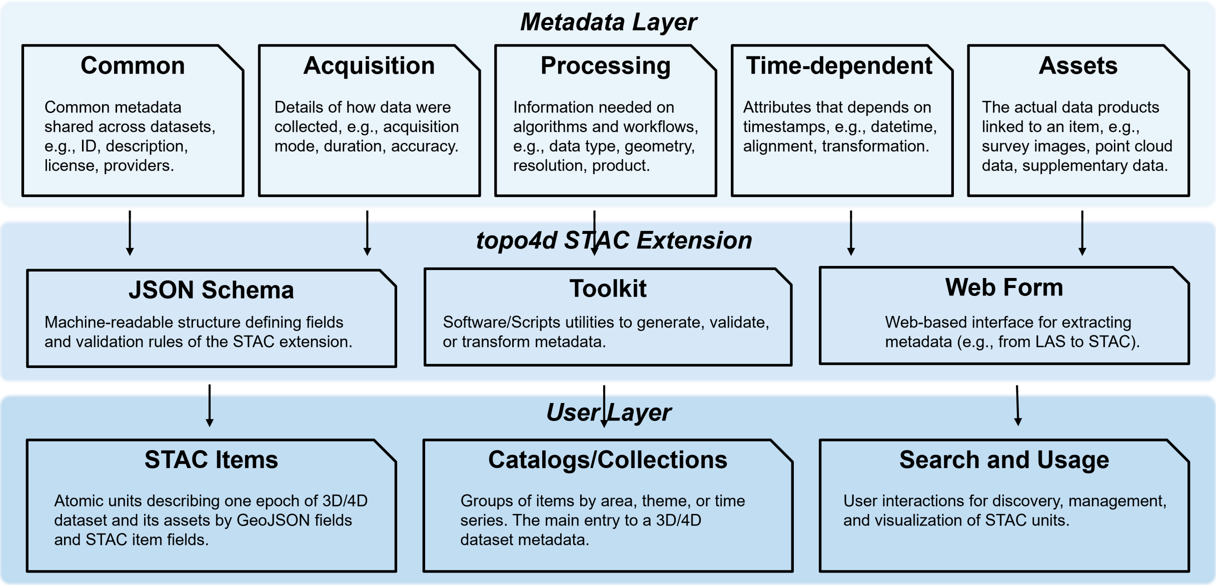

Figure 2. Three-layer architecture of the metadata curation for topographic 4D datasets using the topo4d STAC extension.

metadata such as *title*, unique *id*, *stac_version*, and overall *description*, along with *links* to collections and items. Catalogs may also reference external resources (e.g., documentation, repositories, or processing pipelines) to preserve data provenance and ensure accessibility (Radiant Earth Foundation, 2018).

Within the STAC ecosystem, the catalog enables scalable data publication and interoperability. It allows both users and automated systems to discover datasets through hierarchical navigation or STAC API endpoints, supporting searches across spatial, temporal, and thematic dimensions. Thus, the catalog G establishes the complete metadata hierarchy, connecting curated items and collections into a unified, FAIR metadata structure.

3.3 Metadata Usage

The curated dataset is represented as $\mathbb{D}^* = (M^*, D)$, where $M^* = (G, C, I)$ is the complete hierarchy of metadata linking catalogs, collections, and items to the corresponding datasets D. Once created, this dataset can be accessed through data servers and queried via APIs or web interfaces for analysis.

A published $\mathbb{D}^*$ includes exposing the curated metadata M^* through machine-readable interfaces (i.e., JSON files). The STAC natively supports straightforward deployment via static catalogs (e.g., JSON repositories on web servers or cloud storage) or dynamic endpoints using STAC APIs. Each item, collection, and catalog can support navigation, data download, and integration with existing analysis pipelines or visualization tools. This approach ensures that metadata are ”Interoperable” and ”Reusable” and data assets remain ”Findable” and ”Accessible”, fulfilling the FAIR principles.

The JSON-based M^* enables efficient metadata querying across spatial, temporal, and thematic dimensions. For instance, through the STAC API Filter extension[9], users can perform expressive searches based on item attributes by combining multiple logical and comparison operators within a single query, in accordance with OGC API and Common Query Language (CQL2) specifications. A dataset query can be formulated as a computational search problem:

$$L(R) = \{x \mid \exists y R(x, y)\} \tag{3}$$

where $L(R)$ represents the set of metadata x for which the binary relation $R(x, y)$ is true for a given value y (Teuscher et al., 2025). For example, x is a metadata field, and y is a query parameter or reference value (e.g., spatiotemporal extent, sensor type, product level). The resulting set defines the subset of metadata that matches the specified condition (i.e., where $R(x, y)$ is true), enabling flexible and precise filtering across topographic 4D datasets.

3.4 topo4d STAC Workflow Summary

The proposed metadata curation workflow follows a three-layer architecture connecting raw data sources to a FAIR topographic 4D dataset (Fig. 2). At the ”Metadata Layer”, we harmonize heterogeneous metadata from hosting repositories, local archives, and file headers into a unified dictionary, providing a consistent representation of common, acquisition, processing, time-dependent, and assets information. At the ”topo4d Layer”, we leverage the STAC structure to transform these harvested metadata (e.g., Python dictionary) into standardized entities (i.e., in GeoJSON format), following the proposed topo4d extension. This layer ensures semantic consistency, machine readability, and temporal traceability of 4D datasets by organizing items, collections, and catalogs hierarchically. Finally, the ”User Layer” enables publication and interaction with the curated dataset through STAC APIs or web interfaces, supporting automated search, filtering, and integration with the external systems (e.g., visualization tools, analysis pipelines). Together, these three layers establish a transparent and interoperable workflow that bridges data campaigns, metadata curation, and user interaction. The workflow ensures that FAIR principles are followed while handling complex research metadata for topographic 4D datasets across geoscience disciplines.

4. Application Examples

We showcase two catalogs organizing (1) a multi-source and multi-temporal dataset, and (2) a time series dataset. Practical examples for these two catalogs and usage scripts in the form

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[9] `https://github.com/stac-api-extensions/filter`

of Jupyter Notebooks are provided with the topo4d GitHub repository[10], demonstrating how the catalog becomes a living repository of topographic 4D datasets.

4.1 Catalog 1: Multi-source Multi-temporal Observations of Isar Riverbed

The Isar Riverbed site is a dynamic braided riverbed shaped by sediment transport and human intervention through upstream discharge control through a weir. It is located in Southern Germany, at a natural reserve region of the Isar river (WGS84: 47.5301°N, 11.3090°E) (Fig. 3). The 3D point clouds were acquired using a DJI Phantom 4 RTK (photogrammetry) and a DJI M350 RTK carrying a Zenmuse L2 LiDAR sensor (laser scanning) during repeated surveys from August 2024 to September 2025 (four epochs at seasonal intervals). Point clouds were processed via Multi-View Stereo reconstruction (Schönberger et al., 2016) in Pix4Dmatic (photogrammetry) and LiDAR data were processed in DJI Terra. Topographic surface changes were quantified using the established M3C2 algorithm (Lague et al., 2013). Surface change values are stored as attributes per point coordinate of the reference point cloud in separate files. Complementary PlanetScope imagery from August to November 2024 was retrieved from PSScene[11], providing high-frequency optical observations at daily to weekly intervals that enable near-continuous monitoring of short-term events such as high-discharge periods. All datasets were georeferenced in WGS 84 / UTM Zone 32N (EPSG: 32632) and stored in open formats (GeoTIFF for imagery, LAS/LAZ for point clouds[12]) with accompanying survey documentation.

We organize all data sources into a multi-source, multi-temporal Isar Riverbed catalog G_{Isar}, integrating three collections: (1) UAV point clouds of different sources at multiple epochs, (2) change layers derived from bitemporal point clouds, and (3) satellite imagery time series. We first harmonize unified metadata dictionaries M_{dict} from point clouds and change products, curate them into STAC items following the schema S_{topo4d}, and then group them into different collections C_{UAV}, C_{Change}, respectively. Lastly, we integrate the PlanetScope collection $C_{PlanetScope}$ within the curated catalog $G_{Isar} = (C_{UAV}, C_{Change}, C_{PlanetScope})$. It provides a hierarchical structure that connects point clouds, change layers (i.e., analysis products), and imagery time series over space and time, enabling seamless cross-querying between data sources.

4.2 Catalog 2: Near-continuous 3D Time Series of Kijkduin Sandy Beach

A 3D point cloud time series dataset was acquired by a PLS setup at Kijkduin sandy beach, The Netherlands (WGS84: 52.0705°N, 4.2194°E) during the winter of 2016 - 2017 (Vos et al., 2022). A Riegl VZ-2000 laser scanner mounted on a stable frame overlooking the beach recorded hourly point clouds with densities ranging from 2 to 20 points/m^2. The resulting 2,942 epochs spanning six months were published in the PANGAEA data repository (Vos et al., 2022). The 4D dataset demonstrates great value in spatiotemporal analysis for surface dynamics, such as surface dynamics extraction (Anders et al., 2021) and characterization (Wang and Anders, 2025).

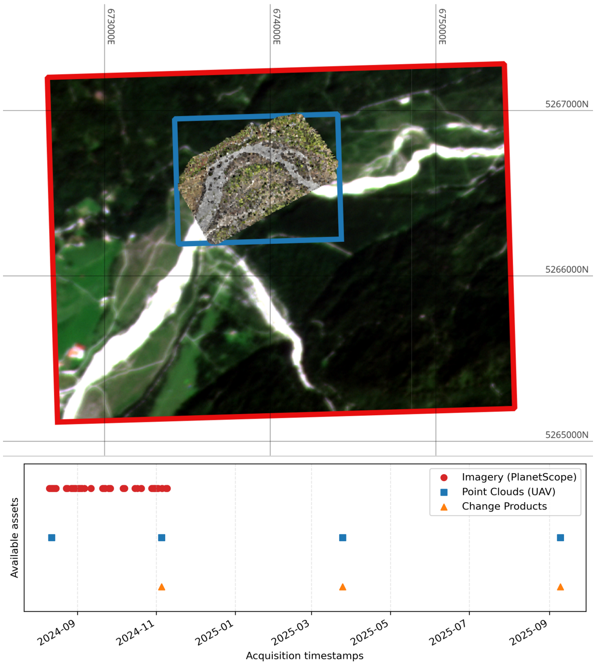
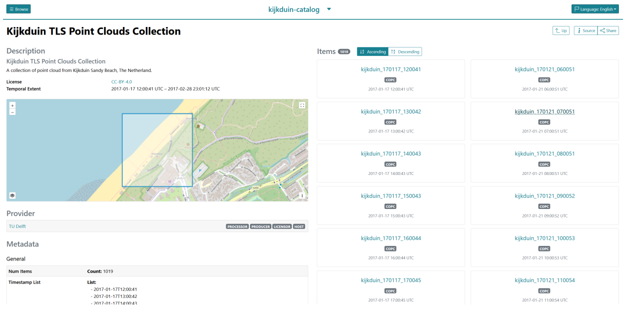


Figure 3. Catalog visualization of the Isar riverbed site, Wallgau, Germany (WGS84 / UTM 32N). The red bounding box shows the spatial extent of PlanetScope imagery, and the blue bounding box delineates the spatial extent of UAV point clouds and surface change products derived from 3D change analysis. The bottom plot visualizes the temporal availability of different data sources.

To render the available metadata interoperable across tools, workflows, and applications, we extract and curate a one-month subset of the full dataset to provide an example STAC collection within the catalog following the schema S_{topo4d}. The curated collection includes 1,019 epochs spanning from January to February 2017, and can be interacted with a web-based tool, e.g., STAC Browser[13] (Fig. 4).



Kijkduin TLS Point Clouds Collection

Description
Kijkduin TLS Point Clouds Collection
A collection of point cloud from Kijkduin Sandy Beach, The Netherland.

License CC-BY-4.0
Temporal Extent 2017-01-17 12:00:41 UTC – 2017-02-28 23:01:12 UTC

Provider
TU Delft

Metadata
General

Num Items	Count: 1019
Timestamp List	List: - 2017-01-17T12:00:41 - 2017-01-17T13:00:42 - 2017-01-17T14:00:43

Items 1019

kijkduin_170117_120041 COPC 2017-01-17 12:00:41 UTC	kijkduin_170121_060051 COPC 2017-01-21 06:00:51 UTC
kijkduin_170117_130042 COPC 2017-01-17 13:00:42 UTC	kijkduin_170121_070051 COPC 2017-01-21 07:00:51 UTC
kijkduin_170117_140043 COPC 2017-01-17 14:00:43 UTC	kijkduin_170121_080051 COPC 2017-01-21 08:00:51 UTC
kijkduin_170117_150043 COPC 2017-01-17 15:00:43 UTC	kijkduin_170121_090052 COPC 2017-01-21 09:00:52 UTC
kijkduin_170117_160044 COPC 2017-01-17 16:00:44 UTC	kijkduin_170121_100053 COPC 2017-01-21 10:00:53 UTC
kijkduin_170117_170045 COPC 2017-01-17 17:00:45 UTC	kijkduin_170121_110054 COPC 2017-01-21 11:00:54 UTC

Figure 4. The collection of a Kijkduin 3D time series subset of one month is visualized via the STAC Browser.

4.3 Use Case Examples

The curated STAC catalogs provide a standardized platform for expanding, exploring, and filtering multi-source topographic 4D datasets through STAC-based APIs. Its hierarchical and modular structure, along with a machine-readable (Geo)JSON-based format, allows automated updates and flexible interoperability based on diverse spatiotemporal analysis demands. Typical examples include:

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[10] `https://tum-rsa.github.io/4D-WORKS/`

[11] `https://docs.planet.com/data/imagery/planetscope/psscene/`

[12] `https://rsa-viewer.lrg.tum.de/scenes/Isar_Riverbank.html`

[13] `https://github.com/radiantearth/stac-browser`

Publishing and sharing: The catalog can be published as a static JSON repository or a dynamic STAC API, allowing online access, version control, and collaboration. The standardized structure allows the catalog to be shared among users and across institutions and communities. Users can download the catalog locally, extend it with their own data, or link it to other STAC-compliant datasets (e.g., imagery time series), thereby enhancing comprehensive multi-modal spatiotemporal monitoring of dynamic scenes across applications and disciplines.

Querying and filtering: Users can perform spatial searches (e.g., finding geospatial data within an area of interest), temporal queries (e.g., retrieving all items between two user-defined timestamps), or attribute-based filtering (e.g., selecting all change products corresponding to the same reference epoch) via the STAC API or Python clients.

Updating the catalog: New acquisitions, data sources, and products can be added by harvesting their metadata, generating new items, and integrating them into the catalog following the same schema. Thus, a catalog can continuously grow, which is especially relevant for continued monitoring applications.

5. Discussion

Metadata curation and management for multi-source topographic 4D datasets remains challenging, as information not explicitly supported in existing formats is easily neglected or lost during manual data curation. Current strategies, adhering to best practices, typically use unstructured text files or supplementary documents that are tedious to parse and maintain. Our proposed STAC-based framework addresses these limitations by preserving metadata in a machine-readable, extensible, hierarchical form that connects topographic 4D datasets with other STAC-compliant resources, such as established satellite imagery time series STAC catalogs or photogrammetry items (e.g., Planet4Stereo; Elias et al., 2025). This interoperability provides the basis for integrated spatiotemporal analysis across spatiotemporal scales. The (Geo)JSON-based modular structure of STAC supports integration with existing geospatial data processing tools and enables systematic curation of common, acquisition, processing, time-dependent, and assets metadata. The topo4d extension emphasizes the importance of temporal evolution and cross-epoch relationships, enhancing the functionality of STAC for comprehensive topographic 4D datasets.

Practical challenges remain in curating and cataloging topographic 4D datasets with our proposed schema. A key point is distinguishing between metadata and auxiliary data, as auxiliary information (e.g., maps, derived layers, thumbnails) may also serve as assets within a catalog. Defining consistent, transparent rules for metadata curation is important for maintaining semantic clarity and reproducibility. However, such rules often rely on prior experience or specific applications. Therefore, data curators remain responsible for carefully designing case-specific metadata strategies. Looking ahead, topographic 4D data management should treat time-dependent metadata as a core and explicit component of dataset creation. Compared to traditional approaches, which are often based on text files and folder structures, the proposed extension and workflow provide a foundation for systematically curating and cataloging metadata with increased interoperability and reusability. By fostering consistent practices across tools and repositories, the topo4d extension contributes to a more unified and FAIR approach to documenting and sharing topographic 4D data.

6. Conclusion

This paper introduces a STAC-based metadata management framework for topographic 4D datasets and proposes the topo4d extension to explicitly curate time-dependent information such as reference epochs, alignment uncertainty and transformation matrices. The strength of embedding the topo4d extension in the established STAC framework lies particularly in the possibility to curate complex multi-source and multi-temporal datasets from a range of sensors (LiDAR, photogrammetry, multispectral, radar) and platforms (ground-based, airborne, satellite) for integrated spatiotemporal analysis in environmental monitoring scenarios. By showcasing the topo4d extension with two real-world catalogs of multi-source riverbed monitoring and high-frequency long-term sandy beach monitoring, we demonstrate that heterogeneous topographic 4D datasets can be organized with an easily accessible and flexible tool towards a more interoperable, reusable manner following the FAIR principle.

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