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Sensor management system (SMS): Open-source software for FAIR sensor metadata management in earth system sciences

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ABSTRACT

Deriving reliable conclusions and insights from environmental observations urgently requires enrichment of the data with consistent and comprehensive metadata, including time-resolved context such as changing deployments, configurations, and maintenance actions. We have therefore developed the Sensor Management System (SMS), which provides a feature-rich platform for modeling even the most complex sensor systems and managing all sensor-related information across their life cycle. Each entity is described via well-defined terms like Devices, Platforms, and Configurations, as well as Sites that are further enhanced with attributes like instrument manufacturers, contact information, or measured quantities and complemented by a continuous history of system-related actions. By further linking the SMS to subsequent systems and services like a registry for Persistent Identifiers (PIDs) or controlled vocabularies (CVs) and establishing a community of end-users, the SMS provides the central element of a digital ecosystem and a transferable solution for practical sensor management across institutional contexts that fosters a more consistent, sustainable, and Findable, Accessible, Interoperable, and Reusable (FAIR) provision of sensor-related metadata.

Metadata

Code metadata.

Current code version	v.1.27.3
Permanent link to code/repository	https://github.com/sensor-management-system
Permanent link to reproducible capsule	https://doi.org/10.5281/zenodo.13329925
Legal code license	EUPL-1.2
Code versioning system used	git
Software languages, tools and services	Python, TypeScript, Django, Vue.js, Nuxt 2, Vuetify, Axios
Compilation requirements / operating environments	Docker, nginx, PostgreSQL/PostGIS, Elasticsearch, MinIO, Keycloak
Developer documentation	https://hdl.handle.net/20.500.14372/SMS-Readme
Support email	sms-core-team@listserv.dfn.de

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1. Motivation and significance

Climate change, biodiversity loss, and environmental pollution increase the demand for comprehensive environmental observations and their long-term interpretation [1]. To address this need, large-scale monitoring infrastructures have been established and expanded, including the European Long-Term Ecosystem, Critical Zone and Socio-Ecological Research Infrastructure [eLTER, 2], the TERrestrial ENvironmental Observatories network [TERENO, 3], and the Modular Observation Solutions for Earth Systems [MOSES, 4]. At the same time, growing sensor densities, increasing data volumes, and emerging applications such as digital twins and AI-enabled Earth-system prediction require sensor observations to be accompanied by comprehensive and reliable metadata [5–7]. Because the usability and trustworthiness of environmental observations depend not only on measured values but also on metadata describing the complete lifecycle of an observation system [8].

Sensor characteristics, calibrations, firmware versions, processing procedures, maintenance activities, deployment histories, and configuration changes can all influence measurements and therefore need to be documented consistently. Only by preserving this contextual information can observed changes be attributed unambiguously to environmental or technical causes. These requirements closely align with the FAIR guiding principles for scientific data management and stewardship [9].

To support consistent sensor descriptions and interoperability, there have been continuous efforts by various communities to develop and establish standards for metadata, data models, and interfaces. Within this context, the Open Geospatial Consortium (OGC) is one of the leading international organizations developing open standards for geospatial interoperability. Its standards include the Sensor Model Language [SensorML, 10] for describing sensors and sensor-related processes, Observations and Measurements [O & M, 11] as a conceptual model for observations, and the Sensor Observation Service [SOS, 12] for accessing sensor-derived data and associated metadata. These standards were brought together within the Sensor Web Enablement framework [SWE, 13,14], which established a common foundation for sensor interoperability and data exchange.

Despite their strengths and comprehensive documentation, SWE-based approaches remain challenging in practice. Their implementation requires substantial knowledge of metadata standards, terminologies, and service interfaces, while many early implementations relied on Simple Object Access Protocol (SOAP) and complex XML-based workflows. Although more recent approaches increasingly use REST and JSON technologies, there remains a lack of user-friendly tools that support the day-to-day management of sensor metadata while remaining compatible with established standards. Consequently, interoperability often exists conceptually but remains difficult to achieve in operational settings.

Operational sensor management presents additional challenges. Research infrastructures frequently involve changing personnel, temporary measurement campaigns, heterogeneous instrumentation, and distributed responsibilities. Without common procedures and dedicated software support, metadata becomes fragmented, incomplete, or inconsistent over time. Recognizing these challenges, initiatives such as TERENO and MOSES have established coordinated data-management concepts and metadata harmonization efforts [15]. However, a central platform for managing, documenting, and tracking sensor metadata throughout the operational lifecycle is still missing.

The Sensor Management System (SMS) addresses this gap by providing a practical platform for managing sensor metadata, deployments, maintenance activities, calibrations, configuration changes, and responsibilities within a single environment. While existing approaches primarily focus on metadata standards, conceptual information models, or domain-specific registries, SMS targets the operational layer by providing a user-oriented and transferable solution for managing sensor systems across institutions. In addition, SMS serves as a key component of FAIR digital ecosystems for environmental time-series data management [e.g., 16].

2. Software description

2.1. Software functionalities

2.1.1. One-stop shop for sensor metadata

A central design choice of the SMS was to provide a single application with which users can manage their sensors as well as all related actions and metadata. This includes a wide range of attributes for precisely describing a system, the integration of contacts and roles for managing responsibilities, the integration of sites, sub-sites, projects and labels for describing complex observatories and measurement networks and also for displaying such networks on a map, the generation of URLs / QR-Codes that point to the respective SMS-entry (e.g., for attaching to sensors and platforms in the field), as well as comprehensive functionalities for mounting devices and platforms within a configuration for mapping even complex systems. As a demonstration of the user-interface, Figs. 1–3 show the landing page of the SMS as well as the overview pages of a *Device* and a *Configuration* (see section 2.2.1 for an explanation), our two main building blocks for modeling complex sensor systems.

2.1.2. Integration of controlled vocabulary

Together with the SMS, we also built a server for a Controlled Vocabulary to handle several lists of predefined terms like equipment types, manufacturers, contact roles, units, measured quantities, and actions. Using this CV across the SMS-instances therefore allows administrators to ensure consistency of the entered sensor metadata. While the CV data model is largely inspired by and also initially based on ODM2 [17], we needed more flexibility to add additional content and information like licenses and countries and also for managing the entries in the CV. Now, we follow a community-approach to populate our CV: new terms and definitions can be proposed directly from within the SMS frontend, which automatically generates an issue in the CV repository [18]. The proposal is then iteratively handled by a team of curators. Once accepted, the new term is added to our CV and becomes available for all SMS-instances.

Interaction with the CV is handled via a JSON:API based API as well as a Python Django (see Code metadata) administration interface (Admin App in Fig. 5) to our curators for add and modify terms and definitions. We further provide a simple web catalog [19] for browsing through the existing entries as well as checking the status of a newly proposed term (Fig. 4).

While we strongly advocate using our community-driven CV to ensure metadata consistency across SMS instances, external vocabularies, and user-defined terminology lists can also be integrated. Since the CV is managed via Django, additional entries or vocabularies can be easily added, for example using fixture files.

2.1.3. PID-generation via B2INST

B2INST [20,21] is a service currently provided by the *Gesellschaft für wissenschaftliche Datenverarbeitung mbH Göttingen* (GWDG) that generates persistent identifiers (PIDs) via an API. The data model follows the schema suggested by the Research Data Alliance (RDA) Persistent Identification of Instruments working group [22]. Currently, the B2INST PID generation is supported for SMS devices, platforms, and configurations. After registering, the items and their metadata are also findable via the B2INST search-portal [23]. Using the B2INST API only requires an administrator to set an Access Token per SMS instance and (optionally) select a B2INST community. Then, all users are able to generate B2INST PIDs directly from within the SMS. While another handle-server could be linked to the SMS as well, we recommend following this workflow as it also archives relevant and standardized metadata with the PID.

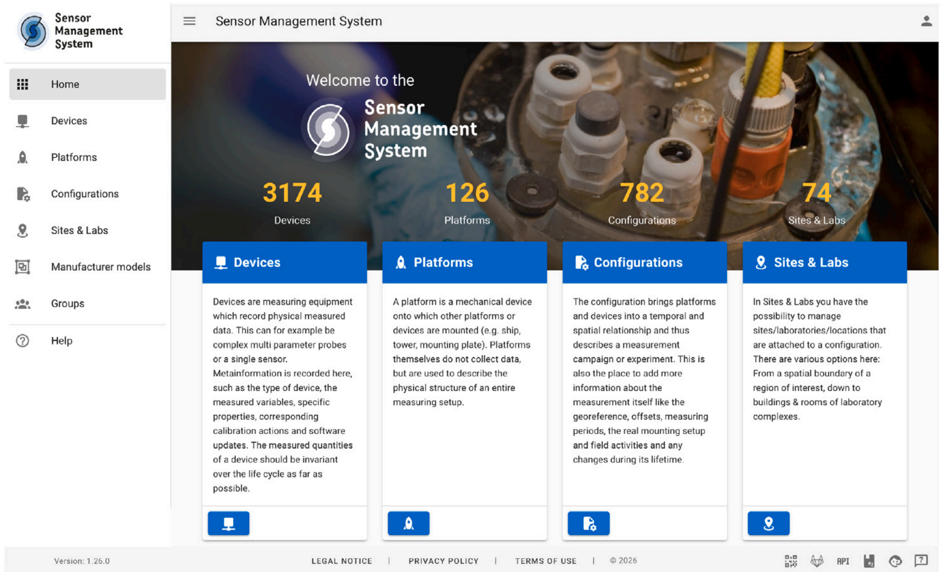

Fig. 1. SMS Landing page of the GFZ-instance showing an overview of the currently managed devices, platforms, configurations, and sites & labs. For quick and straightforward navigation, users can navigate to the respective sections either using the side-menu, or the buttons in the boxes.

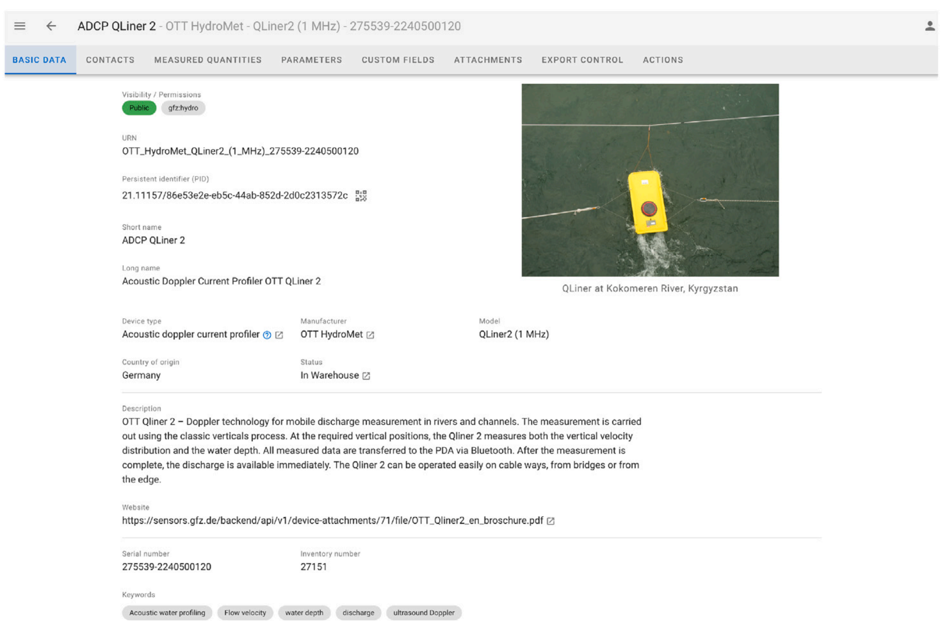

Fig. 2. *Basic Data* Tab of a *Device*, showing the most important attributes. Besides typical information about a device, this tab also shows (if available) a PID including a QR-code, the visibility and permission groups, as well as the serial and inventory numbers.

2.1.4. Simple deployment

As depicted in Fig. 5, SMS depends on several third-party tools and services like *PostGIS* and *Elasticsearch*. In order to ensure a simple deployment of the full SMS on different host systems, we make heavy use of *Docker containers* and provide a *docker-compose.yml*, which contains all required sub-systems and services. Running the core system therefore requires three simple steps:

1. Clone the SMS orchestration repository
```
git clone git@codebase.helmholtz.cloud:hub-terra/sms/orchestration.git
```
2. Load Controlled Vocabulary as Git submodule
```
git submodule init
git submodule update
```
3. Build and run the SMS containers
```
docker compose up -d
```

This starts a “core”-SMS-instance that can be accessed via `http://localhost`. It should be noted that this instance is not yet linked to any additional services (e.g., for registering instrument PIDs) and also uses a highly simplified user- and rights-management. This deployment strategy is a central design decision of the SMS. From the beginning, the system has been developed with transferability in mind, so that institutions can host and operate their own SMS instance in their local environment while still benefiting from shared concepts, coordinated development, and common vocabulary services. In this way, SMS supports

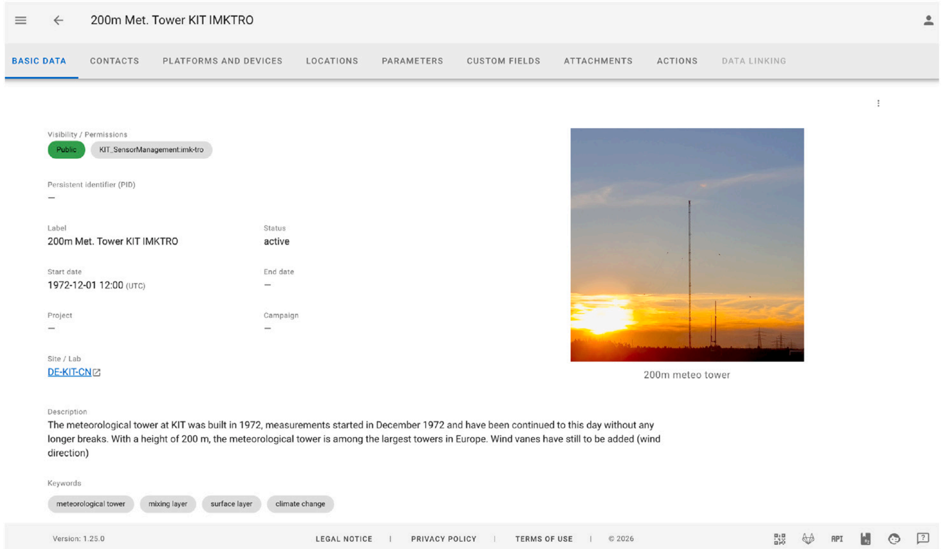

Fig. 3. *Basic Data* Tab of a *Configuration*, showing the current status, the corresponding Site or Lab and a short description.

Compartment	Sampling Medium	General Term	Units	Communities Synonym	Status	Latest	Successor	Global provenance
Atmosphere	Air	Absorbance		• default • GFZ Hydrology	ACCEPTED	✓	-	ODM2 Controlled Vocabularies
Atmosphere	Air	Absorbance, ultraviolet		• default • GFZ Hydrology	ACCEPTED	✓	-	ODM2 Controlled Vocabularies
Atmosphere	Air	Air density	• g/m³ • kg/m³	• GFZ Hydrology ✓ • default	ACCEPTED	✓	-	Wikipedia
Atmosphere	Air	Airflow			PENDING	✓	-	Wikipedia
Atmosphere	Air	Air Pressure			PENDING	✓	-	-
Atmosphere	Air	air_temperature			PENDING	✓	-	CF Metadata Conventions
Atmosphere	Air	Air temperature	• °C • K	• GFZ Hydrology ✓ • default	ACCEPTED	✓	-	NERC

Fig. 4. Example view of the CV-catalog and admin interface, showing the first page of our collected measured quantities, including the implementation status, community-synonyms as well as their provenance.

reuse across heterogeneous institutional settings beyond its original development context.

2.2. Software architecture

The SMS can be considered as a *system of systems* since it includes both its own developments and integrates several third-party tools, e.g., for storing metadata and attachments as well as enabling search and filtering results. The reason for this design choice is that we want to make use of established open-source tools and services whenever possible to keep the SMS flexible and scalable and also benefit from the reliability and continuous improvements offered by these tools. This approach not only accelerates the development process but also ensures that the system can adapt to evolving needs and integrate new technologies as they emerge. In this section, we will focus on our own developments like the data model, frontend and backend, and refer to third-party solutions whenever necessary. A general overview of the architecture is depicted in Fig. 5.

It should be further noted that while similar systems like the O2A Registry operated by the Alfred Wegener Institute [24] have provided important impulses, SMS deliberately follows a transferable and openly deployable design strategy: rather than being tightly embedded into a single institutional infrastructure, it is designed as a community-oriented solution that can be operated, adapted, and further developed across institutions and host environments.

2.2.1. The SMS data model

The whole architecture of the SMS builds on a tailored data model that has been jointly developed with users and informed by their experience with existing sensor management systems like the O2A Registry. A discussion of all SMS data model entities, attributes, and relationships [25] is beyond the scope of this manuscript. We therefore concentrate on the key concepts and relationships that are essential for understanding and practical use of the SMS.

The SMS is based on five entities that describe any sensor system:

- *Devices* are electronic pieces of equipment and are the main entities for sensors, data loggers, etc.
- *Platforms* are pieces of equipment onto which Devices are mounted, like towers or tripods.
- *Configurations* bring Devices and Platforms into a spatio-temporal context. They further describe the exact measurement setup and also track changes to this setup over time.
- *Sites* are regions of interest that can be used to bind Configurations together.
- *Contacts* hold personal information such as name, email, and organization.

To put these entities into context, a climate station can be used as an example. Here, the sensors, e.g., thermometers, pressure sensors, rain gauges, etc., as well as the data acquisition system are added as *Devices*. The tower or tripod, onto which the Devices are mounted, is a *Platform*. The deployment of this station in the field is described through the

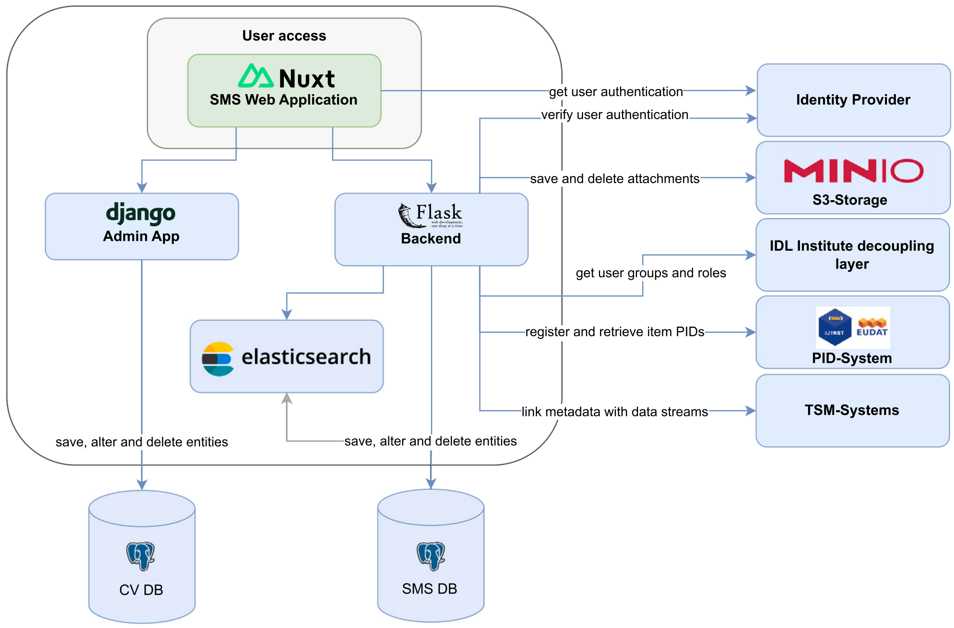

Fig. 5. Architecture of the SMS: The core of the system, consisting of the Web Application, the Admin App, the Backend, and the search engine, is shown within the white box; tools and services that can be linked are shown on the right side, and the two databases where the SMS stores the metadata are shown under the central system.

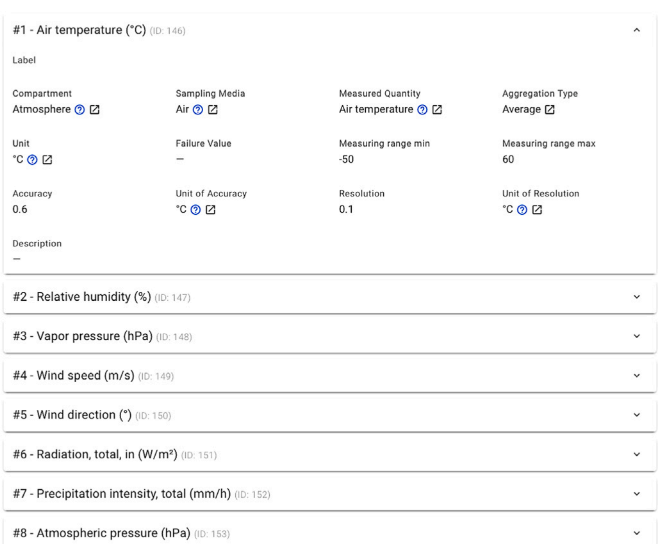

Fig. 6. Measured quantities for a Campbell ClimaVUE50 weather sensor.

Configuration and the location might be further described via the *Sites*. The people who are associated with the station, e.g., technicians or scientists and their roles are added as *Contacts*.

Each of these entities comes with a set of attributes that allows for a detailed description of the particular entity. These attributes are grouped into several sections for improving readability and clarity. Some of these sections are available for all entities:

- *Basic Data* holds the main metadata like name, Unified Resource Names (URNs), persistent identifiers, and descriptions
- *Contacts* contain a list of Owners, PIs, technicians, etc. that are associated with a specific item
- *Parameters* can be used for adding information like, e.g., cable length, dimension, or weight as well as their changes over time
- *Attachments* allow for uploading and storing files like images or protocols. Images can further be displayed directly in the SMS frontend.
- *Actions* hold any kind of event that was associated with the entity (e.g., site visit, calibration, maintenance)

Furthermore, there are several entity-specific compartments that require some more attention:

- *Measured Quantities* for Devices describe which kind of quantity is measured using the device, what unit will be used, as well as measuring range, accuracy, and resolution of the measurement (see Fig. 6). Most attributes here are taken directly from the CV, ensuring naming consistency across the SMS-instances.
- *Locations* are bound to the configuration and can be changed over time. There is the option to model static locations with latitude, longitude, and height according the a coordinate reference system, as well as dynamic locations that will read the concrete location from measured quantities of a device - like data from Global Navigation Satellite Systems (GNSS). Dynamic locations are meant to be used for drones, rovers, vessels, etc. - where we have possibly a different location for every moment we make a measurement.
- *Mounts* describe mounts, modifications, and un-mounts of devices and platforms as well as relative and absolute spatial offsets with respect to the *Locations* of the according *Configuration*. They provide the primary context for modeling complex and interlinked sensor systems. In addition, they store date and time of all these actions, allowing users to monitor and track the status and modifications of a configuration over time. An example for a simple climate station is shown in Fig. 7.

In general, the data model of the SMS has a strong focus on handling and storing *time-dependent* content. As an example, we store the time-period where a particular device is used within a configuration. This is a contrast to approaches that use different *versions* for certain points

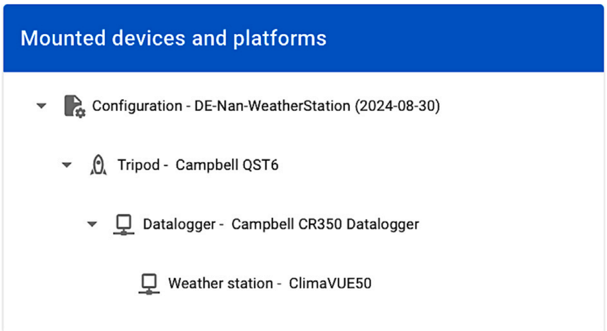

Fig. 7. Example of the device and platform mounts for a configuration.

in time. We think storing the time periods of certain states makes the history of the device visible and improves maintainability – especially in situations where information from the past needs to be considered.

2.2.2. Frontend

The frontend is built with Nuxt 2, which is a meta-framework for Vue and Vuetify as component library. It works as a single page application, allowing the user to log in via OpenID Connect with the Helmholtz ID [e.g., 26]. After login, the frontend is the main system to interact with the backend, making requests via the Axios library. A full list of frontend requirements can be found in the frontend repository [27].

To ensure consistent terminology, the frontend retrieves predefined terms from the CV server for fields such as device types, contact roles, measured quantities, and units. Users can also suggest new vocabulary entries directly from the interface.

2.2.3. Backend

The backend of the SMS is a Flask-based (see Code metadata) Python application and provides a RESTful service following the JSON:API-specification [28]. Almost all of the API-endpoints are based on the resources of the data model, providing GET, POST, PATCH, and DELETE methods for CREATE, READ, UPDATE, and DELETE (CRUD) operations. A full list of backend requirements can be found in the backend repository [29].

The backend stores all of the sensor metadata in a PostGIS database (SMS DB in Fig. 5). Additionally, we store file uploads in an S3 storage bucket based on MinIO (S3 Storage in Fig. 5). To support advanced search options we include an internal Elasticsearch service that stores an optimized copy of the sensor metadata, as well. Using this *Extended Search* and depending on the entity, we can search for all devices from a specific manufacturer or for all configurations of a specific project or campaign. Again, links to the respective dependencies and components can be found in the code metadata.

In addition to pure CRUD operations, the backend also takes care of tasks such as automatically adding an owner contact when the logged-in user creates an entity, keeping track of modification dates, as well as performing more sophisticated validations (e.g., ensuring that one physical device can only be used in at most one configuration at any given point in time).

The backend also provides a connection to a handle system, so that users can mint persistent identifiers (see Section 2.1.3, depicted as PID-System in Fig. 5) and takes care of user authentication, either via API keys or via JSON Web Tokens [30] issued by Helmholtz ID (depicted by the Identity Provider in Fig. 5). The so-called Institute Decoupling Layer (IDL, see Fig. 5) defines user groups and roles, through which the backend filters the accessible entities. If these integrations are not wanted or needed, SMS also ships with Keycloak (see Code metadata) as a simple identity provider and can be linked with a Handle System infrastructure [e.g., 31] for registering entity PIDs.

3. Illustrative examples

3.1. Getting started

For a general introduction to the usage of the SMS, we suggest watching the attached videos; more detailed and comprehensive documentation can be found in the SMS Wiki [32].

3.2. Setting up a device

We illustrate the general use of the SMS by walking through the typical and frequently used workflow of setting up a *device*.

Step 1: Set up basic data. Starting with *Basic Data*, we set a unique *Short name* (required), *Device type*, *Manufacturer*, *Model* as well as the *Serial number* and *Inventory number* (optional). Furthermore, we can generate a *Persistent Identifier*, which automatically sends a request to a connected PID-Service and retrieves the corresponding PID. The main objective here is to give a clear and meaningful description of the device. Naming-consistency across SMS-instances is ensured as predefined terms for Device type and the Manufacturer are taken from our Controlled Vocabulary.

Please note that the device's basic data should not contain any deployment-specific information as it should only describe the device as an object independent of any specific usage context or deployment location.

Step 2: Add measured quantities. The second step is (usually) to enter all *Measured quantities* (see Fig. 6 for an example). By simply clicking on *ADD MEASURED QUANTITY*, we can enter all relevant information for this particular quantity, including a *Measurement compartment* (e.g., Atmosphere), a *Sampling medium* (e.g., Air), a specific *Measured Quantity* (e.g., Air temperature), as well as device-specific parameters like *Unit* (e.g., °C), *Measuring range min* (e.g., −50), *Measuring range max* (e.g, 60), *Accuracy* (e.g., 0.6), *Unit of Accuracy* (e.g., °C), *Resolution* (e.g., 0.1), and *Unit of Resolution* (e.g., °C). Again, most fields can be filled with terms from our Controlled Vocabulary – and this is particularly important for the Measured Quantities as this (ultimately) ensures consistency of variable names across all of our linked instances.

Step 3: Propose a new measured quantity. In some cases, it might be necessary to suggest a new measured quantity. This can be done directly from the SMS by clicking on the small plus-icon next to the respective attribute. In the new window, we can propose a *Term*, a *Definition*, the corresponding *Provenance* and the *Provenance URI* (if taken from another vocabulary). We can further provide a *Category* and a *Note for the curator* to give additional information. Lastly, we can also select a *Global Provenance* from a curated list. After submitting the newly proposed term, the SMS automatically opens an issue in the CV repository, where it is jointly reviewed by our SMS CV curation team.

Step 4: Add additional information. Via *Contacts*, we can define which persons are related to our new Device. By selecting different roles (which, again, come from our CV), we can document who is the *Owner*, who is the *Technical Coordinator* or who is the *PI*. In this, the SMS helps to clarify responsibilities and also makes it easy to update roles when personnel changes occur."

Parameters and *Custom Fields* allow users to add further information about the new device. While *Parameters* are mostly used for describing, e.g., device settings (that might change over time), the *Custom Fields* (usually) describe additional characteristics of the device, which are not included in the basic data or the measured quantities (e.g., supplier or device dimensions /weight).

Step 5: Upload supplementary material. Lastly, we can upload manuals, calibration protocols or images via the *Attachments*-Tab. After clicking on *ADD ATTACHMENT*, we can select the origin of the attachment. Selecting *File* allows users to simply upload a file from their computer, while online resources can be linked by selecting *URL* and adding the respective address. By selecting the checkbox at the bottom of the attachment-form, we can even show uploaded/linked images directly in the Basic Data tab.

4. Impact

As demand increases for inter-institutional research data management and projects, as well as FAIR, open, and reproducible data, it is obvious that consistent and standardized metadata play a crucial role in this cultural change. This holds particularly true for observational and sensor-based data, for which further information about accuracy, device calibration, etc. needs to be taken into account when working with such data. By making sensor context explicit and time-dependent (e.g., setup changes, maintenance, calibrations, deployments), SMS enables more robust downstream analyses and supports new cross-site and cross-institutional research questions that rely on comparable, traceable observations. The impact of our SMS in this context can therefore be summarized as follows:

4.1. FAIR and sustainable sensor metadata

SMS promotes FAIR sensor metadata by providing a standardized, time-resolved description of sensor assets and deployments, thereby improving metadata consistency, interoperability, and reproducibility across research infrastructures. Continuous action histories improve transparency, support interpretation of sensor-derived data, and reduce information loss during staff turnover. Integrated PID generation and controlled vocabularies further strengthen metadata interoperability and reusability.

4.2. Central system for managing sensor metadata

As of today, more than 7000 devices, 300 platforms, 1200 configurations and 200 sites/labs are managed across the four publicly available SMS-instances at the Helmholtz Centre for Geosciences, the Karlsruhe Institute of Technology, the Forschungszentrum Jülich, and the Helmholtz Centre for Environmental Research. A list of all currently running SMS instances is compiled in Table 1. Being members of the Helmholtz Association's research field Earth and Environment, these centers conduct environmental research and operate large-scale observation systems and monitoring networks. Hence, joint infrastructure projects like TERENO now rely on the SMS as their central framework for managing sensor-related metadata. SMS therefore serves as the central metadata platform for several large-scale environmental monitoring infrastructures and supports operational workflows such as calibration tracking, maintenance documentation, and deployment management.

4.3. Multiple instances - one community

At present, there are production instances of the SMS at four Helmholtz institutions including a publicly accessible SMS-Sandbox (see Table 1) for workshops and training courses. Beyond this original context, the SMS is also operated within the eLTER Research Infrastructure and initial transfer activities beyond Helmholtz have started. As an example, one instance of the SMS is already running at the British Oceanographic Data Centre (BODC, see Table 1), demonstrating that the system can be transferred to and hosted in other national and institutional settings.

The deployments of the German instances are coordinated by the SMS core team, which helps us to a) ensure a straightforward integration in different host systems, and b) track issues for improving the robustness of the SMS. A central objective of the SMS is therefore not only harmonization, but also transferability. The system is distributed as a Docker-based deployment (see section 2.1.4), which facilitates local operation by different organizations on their own host systems, while still benefiting from shared concepts, coordinated development, and common vocabulary and PID services. In order to streamline and coordinate the growing number of users, we have initiated monthly *SMS community meetings*, where users can ask questions, provide feedback or discuss concepts and best-practices for integrating complex sensor systems. These community meetings have since become a central tool for ensuring a user- and community-driven development of the SMS. This community-driven coordination is particularly important to harmonize documentation practices across institutions and to ensure that evolving requirements from operations and science are reflected in the software.

Table 1
List of productive SMS instances.

Instance	URL
GFZ	https://sensors.gfz.de
KIT	https://sms.atmohub.kit.edu
FZJ	https://sms.earth-data.fz-juelich.de
UFZ	https://web.app.ufz.de/sms/
SMS Sandbox	https://sensors-sandbox.gfz.de
BODC	https://pid-sms.bodc.uk

4.4. The SMS as central element of a digital ecosystem

Around SMS, there is an ongoing development of tools and services to promote complete digital ecosystems for time-series data [16,33]. In this context, SMS acts as a metadata backbone that provides harmonized, time-resolved sensor context to downstream infrastructures and services. This includes the System for Automated Quality Control [SaQC, 34,35], full-fledged data management frameworks like, e.g., *time.io* [36], the SensorThings API [37] as central data interface for environmental sciences via the STAMPLATE-project [38] and, in particular, the so-called STAMPLATE-Schema [39], which enhances the generic STA data model with additional information that can be directly retrieved from the SMS, and the so-called *Earth Data Portal* [40] as an overarching data portal and main point of entry for data discovery and exploration of connected research centers.

In these ecosystems, observational data are typically stored and served by external data infrastructures rather than by the SMS itself. The SMS contributes the corresponding sensor metadata and supports the association of measured quantities of devices within a configuration with external STA-like data endpoints. Users and downstream services can thus combine time-series observations retrieved from external systems with the time-dependent sensor context managed in the SMS. However, it should be noted that while initial developments towards a generic and widely usable integration of typical data endpoints exist, current implementations still rely on institution-specific solutions due to heterogeneous data models and interfaces.

Together, these developments position the SMS as a key contributor to a consistent and FAIR research data infrastructure, particularly for environmental sciences. By exposing standardized interfaces and enabling PID-based linking across instances, SMS supports scalable integration of sensor metadata into publication, discovery, and analysis workflows.

5. Conclusions

Environmental observations increasingly require metadata that captures the evolving context of sensor assets and deployments throughout their lifecycle. To address this need, we developed the Sensor Management System (SMS), a platform for managing sensor metadata, operational histories, and deployment information within a unified environment.

By representing systems through the entities Devices, Platforms, Configurations, and Sites, SMS provides a consistent description of complex sensor infrastructures. Time-resolved configuration and action histories enable reconstruction of system states for specific observation periods and thereby support the interpretation and reuse of observational data. Container-based deployment, coordinated multi-instance operation, and an active user-community facilitate adoption across institutions and heterogeneous infrastructures.

Ultimately, SMS provides a practical solution for managing sensor metadata and operational information throughout the lifecycle of environmental observation systems. By supporting PID registration, continuous tracking of system-related actions, and the use of controlled vocabularies, SMS promotes metadata consistency, traceability, and interoperability while supporting modern research data management practices. Although originally developed within the Helmholtz Earth and Environment research field, SMS was designed as a transferable platform for operational sensor management. Its container-based deployment, coordinated multi-instance operation, and current use across four Helmholtz institutions, as well as initial deployments in international observation networks such as eLTER and BODC, demonstrate its applicability beyond a single organizational context. As a metadata backbone that can be integrated with downstream time-series infrastructures and discovery services, SMS lowers barriers to metadata harmonization and cross-institutional data reuse. In this way, SMS contributes to more consistent and FAIR sensor metadata management and supports the long-term usability of environmental observations.

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CRediT authorship contribution statement

Christof Lorenz: Writing – review & editing, Writing – original draft, Supervision, Software, Project administration. **Nils Brinckmann:** Writing – review & editing, Writing – original draft, Supervision, Software, Methodology, Conceptualization. **Jan Bumberger:** Writing – review & editing, Funding acquisition. **Marc Hanisch:** Writing – review & editing, Software, Project administration. **Tobias Kuhnert:** Software. **Ulrich Loup:** Writing – review & editing, Supervision, Software. **Rubankumar Moorthy:** Software. **Florian Obsersteiner:** Writing – review & editing, Software. **David Schäfer:** Writing – review & editing, Supervision, Software. **Thomas Schnicke:** Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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