Research Article

Integration and management of sensor data for rainfall monitoring

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Abstract

Meteorological observation systems are extremely data-driven. However, several factors affect measurements, which require the use of environmental metrology techniques to increase the quality of measurements, decrease errors and evaluate measurements uncertainty. In this paper, we propose and develop a framework that integrates, process and visualizes sensor data and its associated metadata (for rainfall monitoring). This task is accomplished with a workflow designed to correct raw sensor data, which uses an elastic stack based infrastructure to collect, transform, and store sensor data and metadata. We validated our framework using real precipitation data from a Tipping Bucket Rain Gauge.

Keywords Rainfall monitoring · Metrological metadata · Meteorological sensor · Data processing · Tipping Bucket Rain Gauge (TBRG)

1 Introduction

Monitoring and analysis of weather and climatic conditions relies on the processing of atmospheric conditions data, in which the weather stations play an important role. Observations sensor data has wide use in weather forecasting and climate studies.

In weather forecasting, they are important for creating synoptic charts or informing the atmospheric variables to numerical models. Sensor data describes the evolution of a certain observed meteorological variable over time. The results of weather forecasts are increasingly available to people and influence their lives [1].

A field meteorological observation refers to a standardized procedure to describe an environmental parameter at a given time. Several types of measurement systems compose a meteorological observation system that collects observation data about wind, air temperature, relative humidity, pressure, precipitation, solar radiation, and others [2].

A meteorological observation system should be able to promote the global exploration of the atmosphere in a timely manner, since this information must be made available for analysis related to a meteorological occurrence [3].

Measurements need to follow specific procedures and are always affected by several types of errors. In order to perform a measurement without errors it would be necessary: a perfect measurement system, a controlled and perfectly stable environment, a perfect operator, and that measurement has to have a unique, perfectly defined and stable value [4]. Thus it is impossible to execute an error-free measurement.

Metrology is the science that aims at supporting concepts and practices related to measurement in any field of application. It has the role of conducting actions toward reliable measurement results. It offers techniques for

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increasing the quality of measurements, decreasing errors and evaluating measurement uncertainty [5].

Several factors affect measurements (M) that is obtained through a measuring instrument or system, also referred to as raw data. The correction factor (C) of a measurement system (systematic errors) can be used to correct systematic errors. Other factors (random errors), such as random errors and expanded measurement uncertainty (U), should be tied to the measurement. An error consists of the difference between a measured value and its true value. The uncertainty can assume any value in a range [6].

According to the World Meteorological Organization (WMO), the complete environmental observation system (sensors and data acquisition system) must be calibrated periodically [7]. Calibration in a first step is the operation that establishes, under specified conditions, a relationship between the values and measurement uncertainties provided by standards and the corresponding indications with the associated uncertainties. In a second step, it uses this information to establish a relationship to obtain a measurement result from an indication [5].

Using calibration, the measurement (M) of a variable becomes the Measurement Result (MR), as described in Eq. 1. Using correction factor (C) added to M will have the corrected measurement. The measurement Uncertainty (U) is non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information and it is evaluated according to the Guide EA-4/02 [8]. MR is the set of values assigned to a measurand (range corresponding to the measurement results), along with all other pertinent information available [5]. In this case, we will have the measurements corrected with the associated uncertainties.

Some documents contain information about C and U values, such as calibration certificate document or user's guide. They are used to compose the Measurement Result (MR), expressed by $MR = M + C \pm U$ [9].

The environmental observations require additional information about the context in which they were collected. Metadata represents an important information about who conducted the observation, and what, where, how, and why it was measured. It is any kind of data that describes data under some aspect [10].

According to [11], "if we measure rainfall, in order for the data to be useful for future users, we also need to document where and how the measurements were made. Stations documentation refers to the information about the data or metadata. Ideally, a complete metadata should register all the changes a station has undergone during its lifetime, composing what is called the station history".

The person who manages meteorological network should consider the development of a metadata database as a high priority, since it gathers all the information related to the installation, maintenance and observation program of all the meteorological stations [12].

Considering the presence of metadata, two scenarios can be evaluated: (1) metadata exists or (2) missing or scarce. The first scenario allows traceability, data correction, uncertainty evaluation, metrological treatment, and quality control, which can lead to a more assertive decision-making. The possibilities observed in the first scenario cannot be guaranteed in the second scenario.

Users of environmental information need information about the instrumentation used, geographic coordinates, raw measurements, and others. Details about the installation, maintenance and calibration history are important and can be used to achieve scientific conclusions and make decisions [6].

Some research aims at data quality and accuracy, which involves calibration of sensors and metadata tracking [13–17]. Our work has focus at providing means to obtain higher quality data from metadata, providing long-term capabilities of calibration and traceability of measurements conducted using our system.

Motivated by such challenges, in this paper, we propose a framework that allows the integration and processing of sensor data and its associated metadata (for rainfall monitoring) with several possibilities for processing, analysis and data correction. Our contributions includes:

1. The implementation of an infrastructure to collect, transform and store data and metadata;
2. The development of a workflow to integrate data and metadata and correct raw sensor data using its metadata;
3. The development of the Visual Information Analyzer (VIA) software for sensor data visualization;
4. The framework validation using precipitation data from real sensors.

The remainder of the paper is organized as follows. We introduced the rainfall monitoring system used in this work in Sect. 2. We present the workflow process for sensor data management roles in Sect. 3 and the infrastructure for data processing, storage and manipulation is shown in Sect. 4. Section 5 presents the Visual Information Analyzer (VIA). The accomplished results are described in Sect. 6. Finally, Sect. 7 presents the conclusion and future work.

2 The rainfall monitoring system

American Meteorological Society [18] defines precipitation as all liquid or solid phase aqueous particles that originate in the atmosphere and fall to the earth's surface. The main type of precipitation is rain. However, it can occur in the

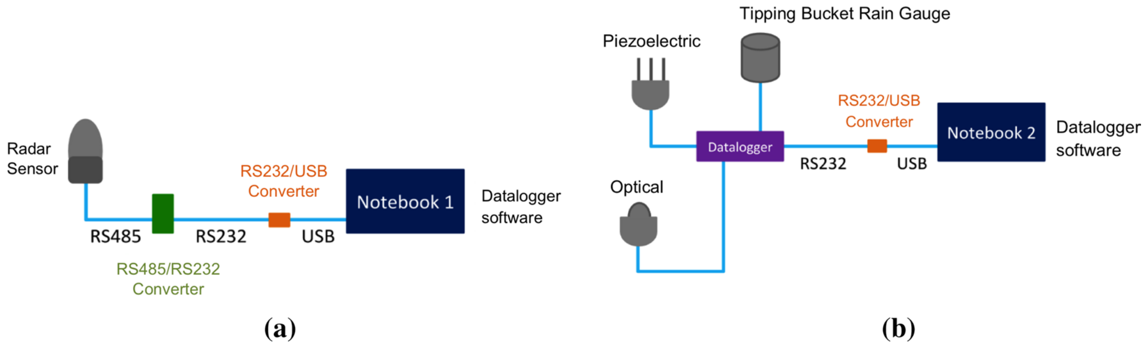

Fig. 1 Overview of the data measurement and communication system

form of hail, snow, rain with snow, snow pellets, and snow grains.

The precipitation measurements support the understanding of the hydrological cycle and how it influences weather and climate. Therefore, its importance is observed on conducting studies for weather and climate forecasting, and detection of extreme events [19].

Flood is one of the major consequences of precipitation. The occurrence in inhabited areas can cause great damage, including loss of human lives [1].

We have performed an experiment to collect environmental data by measuring the amount of rain in millimeters (mm) using four sensors. Each one has different technology and operation mode: mechanical, optical, piezoelectric and radar.

The mechanical sensor (A) is a Tipping Bucket Rain Gauge (TBRG) that uses scales to measure rainwater. Other sensors can identify size, velocity, quantity, and shape of water droplets. The optical sensor (B) uses light beams, the piezoelectric sensor (C) uses the piezoelectric effect, and the radar sensor (D) uses the Doppler effect.

Figure 1 shows the data measurement and communication system, which provides sensor data collection in real time. The radar sensor (a) connects directly to a computer. The mechanical, optical and TBRG sensors (b) connects to the data logger and then to a computer. Sensor data are stored as CSV (Comma-Separated Values) files.

The data files usually have a column-oriented representation to store timestamp and measured values. Each line represents several meteorological variables, including the amount of rainfall accumulated per minute and equipment technical data.

Different manufacturers and sensor models have different file structures. We also observed heterogeneity between the different sources, format and types of sensor metadata.

The metadata sources includes technical manuals, user guides, manufacturer's website, calibration certificate and information gathered from sales representatives. In addition to this, metadata is also produced during the execution of the experiment.

We categorized the metadata collected for the experiment sensors of this work in five types: manufacturer's technical specifications, calibration certificate, geographic location, installation and others.

We have installed these sensors in a metal tower placed in the city of Cachoeira Paulista, SP, Brazil, at the geographic coordinates of 22° 41′21.12″ S and 45° 0′22.96″ W. Their arrangements and placement follows the standards required for instrumentation installation, such as sensor spacing, communication method, obstacle distance and protection against external interference [7]. Figure 2 shows the infrastructure used to collect rainfall environmental data.

3 Sensor data management roles

A wide variety of observational practices affect meteorological data, including the instrument, its exposure, recording procedures and many other factors. The best

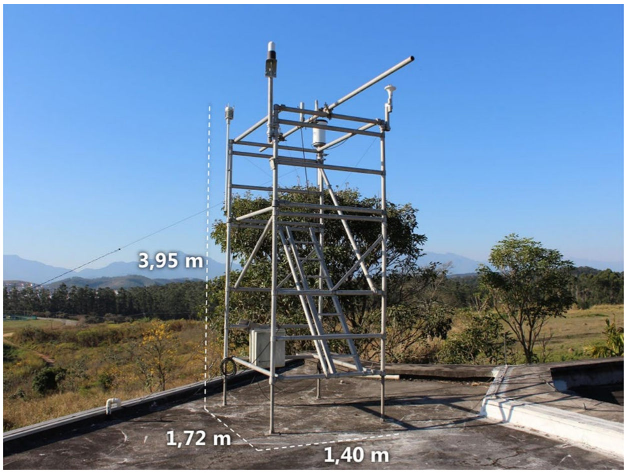

Fig. 2 The rainfall monitoring system

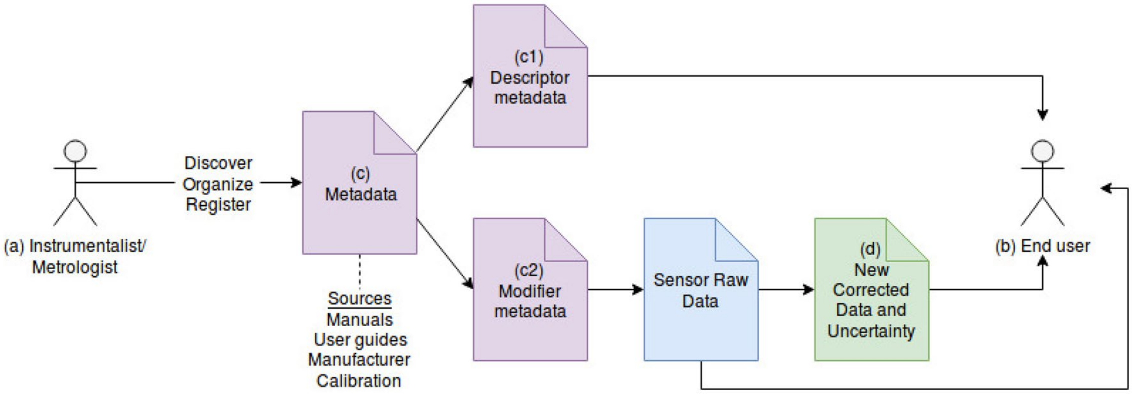

Fig. 3 Sensor data and metadata workflow

possible usage of the data requires keeping record of all these metadata [11].

According to [20], raw sensor data has limited usage without any metadata that describes it. As a consequence it is hard to discover, integrate or interpret data without its metadata. Metadata can be used to process and improve the raw data. However, metadata are generally dispersed in different sources.

The task of installing and operating sensors is far from fully automated. The implementation of a new sensor requires an instrumentalist to install the equipment and a metrologist to perform the sensors calibrations. During the sensor implementation, procedures generate important metadata that needs to be propagated along with the data.

Professionals involved in sensor deployments have vital importance to discover, organize and record the relevant metadata. There are two well-defined user roles in the workflow: instrumentalist/metrologist (a) and end-user (b). Figure 3 shows sensor data and metadata processing workflow, including users roles and their relation with metadata.

Instrumentalist has knowledge about the measuring system. He can gather metadata about the manufacturer's technical specifications, inform the geographic location of equipment, explain the installation procedure, provide operation information, record important occurrences, and report the equipment status. On the other hand, metrologist can provide calibration data, along with calibration certificate, history, inform the correction method and uncertainty assessment to be applied to the data.

End-users comprise meteorologists, students, civil security professionals and others. They use data and metadata for a variety of purposes. A single person can assume the roles of instrumentalist and metrologist to provide information to the system, and also play the end-user role.

The metadata (c) reported by Instrumentalists/Metrologists are classified as Descriptor metadata (c1) and Modifier metadata (c2). Descriptor metadata contains characteristics about the sensor and its data, which includes sensor name, sensor model description, measurement range, and operation logs.

Modifier metadata contains information about procedures and values that can generate new corrected data and uncertainty (d) from the sensor raw data. Some examples include correction values provided by the calibration certificate, procedure for using the values for correction, evaluation procedure, and visualization of measurement uncertainty.

End-users are allowed to view and download descriptor and modifier metadata. VIA can use modifier metadata to process data.

4 Infrastructure for sensor data management

The measuring system used in this paper consists of a TBRG connected to the digital ports of the data logger, which collects the sensor data. A serial RS232 interface connected to a computer allows data retrieval from the data logger, controlled by software developed using Loggernet[1] by Campbell Scientific.

For each amount of rainfall (0.2 mm for example), in case of rain measurement using a TBRG, an event is recorded in the data acquisition system (data logger) and contains the timestamp (date, hour, minute, second) and one tip (0.2 mm). From this information it is possible to calculate the accumulated rainfall (amount per hour, day,

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[1] https://www.campbellsci.com/loggernet.

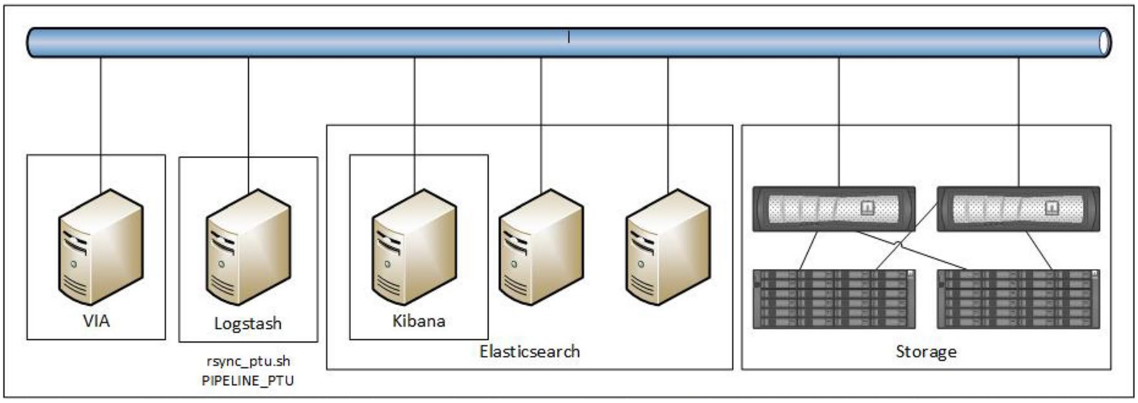

Fig. 4 Infrastructure for data processing of online monitoring

month and year in mm) and rainfall intensities in mm/h (the average is calculated every 1 min).

The Loggernet stores sensor data in files encoded in ASCII format with a header and the measurements. The gathering date and time is embedded into every data collected, separated by commas. We collected 11.4 MB (~ 13 Bytes/s) of data for the period from 19/12/2016 to 28/08/2017.

The notebook has an Internet connection and Secure Shell (SSH) configuration for external access. In this way, external clients can collect sensor data by accessing its file system.

We have developed a system to periodically access and reads the raw data files through an SSH connection. It makes the file available in an area accessible by the search engine Elastic Stack,[2] a NoSQL database management systems dedicated for searching, indexing and analyzing data in real-time, used for the operation of the expanded online monitoring [21].

Elastic Stack is a set of highly scalable tools, comprising Elasticsearch, Logstash and Kibana, suitable for storing and retrieving large volumes of heterogeneous data. We added to this storage the sensor metadata in a flexible data structure [22]. Its data treatment foundations focus on log files and follow the same structure found in the treatment of data files produced by sensors, as well as in near real time manipulation by the measurements.

Logstash[3] allows the collection and processing of data from a variety of sources and formats, defined in configuration files. The data received by Logstash is structured and can be submitted to various types of processing, such as data type conversion, private field removal and geographic coordinate conversion [23].

Elasticsearch[4] allows the storage of data handled by Logstash. It has an index-based storage with search and analysis mechanisms. Elasticsearch has a REST API for data access.

We have configured a Logstash instance with a pipeline that identifies file changes and performs data collection procedures. Next, Elasticsearch is responsible to index and storage of data. Kibana provides visualizations and dashboards to administer its resources and also online access to sensor data (via Web System with VIA).

We have used an already deployed computational infrastructure with version 5.2 of Elastic Stack. It consists of dual Quad-core servers @2.27 GHz and 32 GB of memory each (Fig. 4). Logstash and VIA used dedicated servers. We opted for using cluster of three servers for Elasticsearch. The implementation a cluster guarantees an increase of performance, horizontal scalability and availability using data distribution and dynamic load balancing features of Elasticsearch. One of the cluster nodes was shared with Kibana.

For storing the data we used a 100 TB NetApp storage, deploying a 2 TB of virtual storage to each server. The current architecture (Fig. 3) provides mechanisms to store NetFlow and file transfer log data from the CPTEC data center, implemented with a NetApp storage.

Initially a single server infrastructure configuration was used to analyze file transfer data logs [24] and meteorological data [21]. Later, we have to upgrade this infrastructure since the amount of NetFlow data generated by the main switch required a cluster configuration of three nodes to provide performance, scalability and availability. At that time we have achieved an ingestion of a maximum of 40,602,491 network flows in 1 day [25].

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[2] https://www.elastic.co/products.

[3] https://www.elastic.co/products/logstash.

[4] https://www.elastic.co/products/elasticsearch.

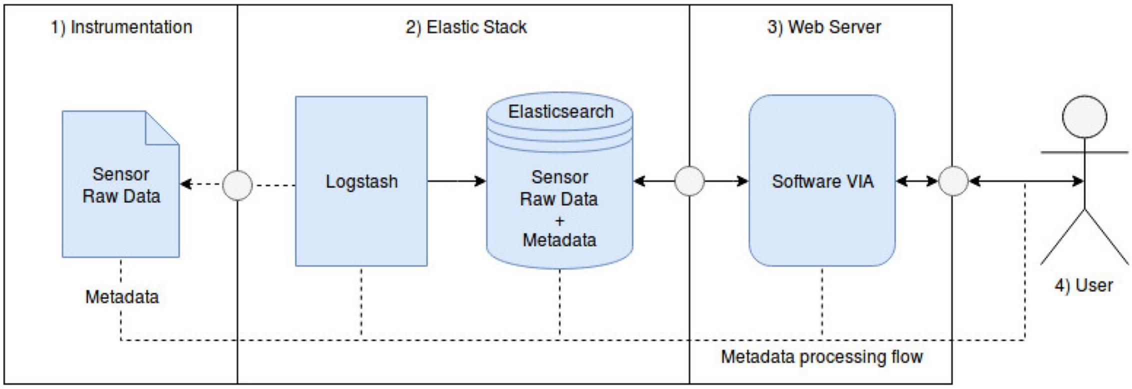


Fig. 5 Sensor data management workflow

We have developed a workflow with three steps (Fig. 5) for data and metadata integration, according to the location and state of data processed: instrumentation (1), data treatment and storage using Elastic Stack (2), and the application on a Web Server (3).

The first step (1) involves the Instrumentation and occurs after the selection, installation and configuration of the measurement system. The equipment begins to operate and generates raw data from environmental conditions after sensor deployment.

This step relies heavily in the knowledge of an Instrumentalist or metrologist. Their tasks include performing the operational work of maintaining the instrumentation equipment, and supervising the operation and quality of the measurement system and its data.

The implementation and operation of the sensor provides important information that is stored throughout the life cycle of the equipment and its operation. Most metadata discovery occurs at this stage.

We used the rainfall monitoring experiment, presented in Sect. 2, to validate this step. Instrumentation, metrology and metadata survey procedures were conducted to the implementation and operation of the sensors.

The second step (2) includes the environment with Elastic Stack and contains the tools for handling and storing data and metadata. It is triggered when sensor generates new raw data and the data logger records into the data input files (saved on the filesystem).

In this approach, new data is appended to the data input file that triggers Logstash to read and transform the new raw data according to the configuration file. Next, it forwards to Elasticsearch.

At this moment, each measurement corresponds to a JSON document, belonging to an index represented by the related sensor. Afterwards, Elasticsearch index and stores the data, which is ready for retrieval through a REST API.

We have created custom Logstash configuration for each of the four rainfall monitoring sensors, which allowed data ingestion in Elasticsearch. The Logstash allows configuration setting for collecting sensor data, transforming textual values into numeric values, removing the decimal point, and converting the date, time, and time zone formats.

The flexible infrastructure of Elasticsearch allowed the storage of the heterogeneous raw data of these sensors. A copy of the raw data was stored to remove any doubts about the state of the original data.

The third step involves an application on a web server (3), the Visual Information Analyzer (VIA) software, accessed by the user (4).

5 Visual information analyzer (VIA)

A weather station or equipment usually has different sensors that collect meteorological parameters. We have developed VIA as an interface to the meteorological sensor information. It has different access permissions for Instrumentalist/Metrologist and end-users roles (Table 1).

The Instrumentalist/Metrologist role has an interface with forms for sensor metadata recording and editing. Generally, it requires basic equipment identification information. Other metadata is optional and depends on availability.

In order to make the information available to the end-user, VIA allows the Instrumentalist/Metrologist to define the access permissions of the variables to be visualized by the end-users.

On the other hand, the end-user interface allows three options for viewing sensor data series: raw, corrected, and corrected with measurement uncertainty. It also allows the download of information.

Table 1 Instrumentalist/metrologist and end-user roles

Role	Role detail	Access permission	
		Instrumentalist/metrologist	End-user
Sensor metadata	Descriptor metadata	Record Edit Read Download	Read Download
	Modifier metadata		
Sensor data series	Raw	Read Download	
	Corrected		
	Corrected with measurement uncertainty		
Control the variables to be visualized	–	Full	Limited

The Sensor Calibration Certificate provides metadata information about Correction factor (C), Uncertainty (U) and k factor [26]. VIA corrects measurements M (raw data) using C and associates U, through linear interpolations. With interpolation it is possible to construct a new data set and generate the graphs from a discrete dataset of values previously known in the Certificate of Calibration [27].

The reported expanded measurement uncertainty in the Sensor Calibration Certificate is the combined standard uncertainty multiplied by the coverage factor "k" for a confidence level of 95.45% and was determined according to [9, 28]. In VIA, we have used the Eq. 1 for the elaboration of the graphs:

$$\mathrm{RM} = (\mathrm{M} + \mathrm{C}) \pm \text{expanded measurement uncertainty U} \tag{1}$$

When users request information using VIA, queries to data and metadata are performed, along with data processing. Raw data, corrected data, and uncertainty are displayed in charts, formatted with the JavaScript Chart.js library. The values are transferred using JSON format.

The Elasticsearch stores sensor data information using indexes with the prefix ".via", created to allow the persistence of data using indexes. Copies of the sensor metadata are stored in other indices.

The VIA development used Python and the Django web framework. Its development required a medium length and complexity programing code. Python objects query the sensor raw data and their metadata through the REST API provided by Elasticsearch and perform the correction and uncertainty calculations. The raw data, metadata, and new calculated data are handled by Django and displayed on intuitive web pages to the end user.

It is important to note that the entire workflow is very rich in the production of useful metadata. In addition to the metadata collected and produced in the instrumentation step, the other steps also produce metadata that is stored.

Logstash generates metadata about the data processing processes. For instance, this can be used to track which host produced the data, at what time it was processed and if an error occurred. VIA also stores metadata about changes and request history.

6 Results and discussion

We have used VIA (Fig. 6) in the third step of the sensor data management workflow, which allows users to visualize and manipulate the results.

The specialist or someone who has access to the information needs to inform the metadata about the equipment. The storage of a sensor metadata can be conducted in four stages: insertion of metadata, variables classification, correction method and adjustment. Figure 7 shows the VIA interface that allows insertion of sensor metadata.

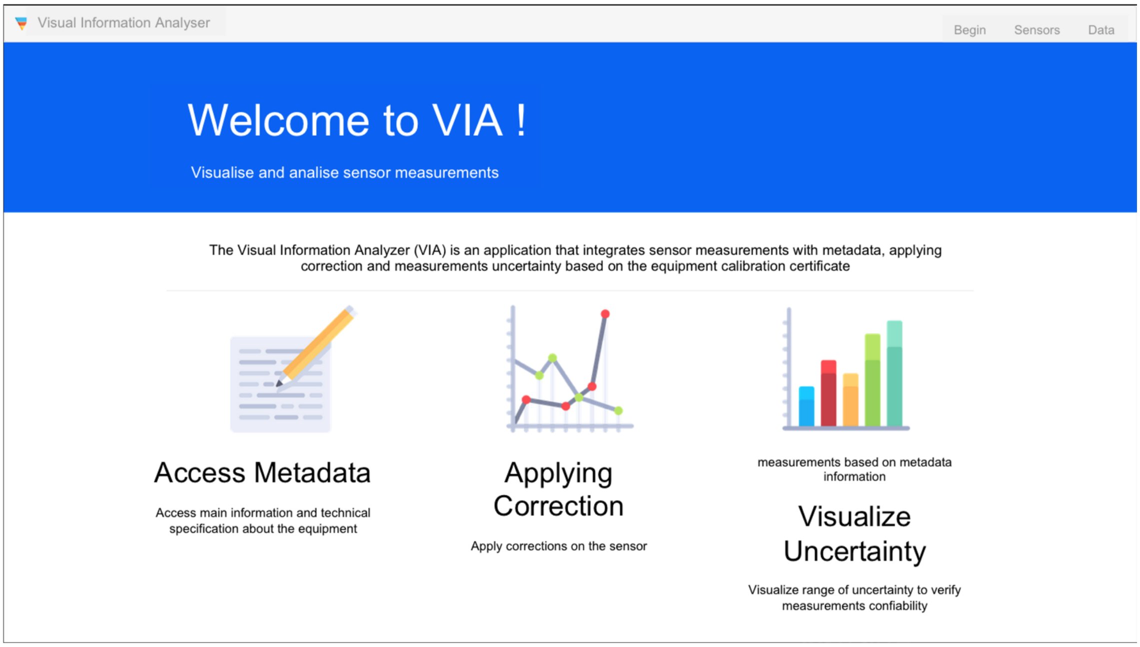
The description metadata of all rain sensors were stored using the VIA interface input via VIA forms. The calibration certificate and the necessary information for correction and uncertainty assessment were only available for sensor A, so its data was used as reference for the validation of this workflow stage.

VIA allows users to access sensor data using geolocation. Sensor geographic coordinates are provided during insertion. It allows search of metadata and visualization of sensor location based on its location.

We have stored data in Elasticsearch from the four rainfall sensors used in this experiment. However, we only presented information from sensor (A) in this section, which has all the necessary metadata for the evaluation of measurement uncertainty over the entire period. VIA allows the usage of metrological features and uncertainty visualization. It has three options for viewing and downloading sensor data series: raw, corrected, and corrected with its associated measurement uncertainty.

Figure 8 shows the data correction visualization in an accumulated rainfall chart. The blue line corresponds to raw sensor data. The red line corresponds to the corrected data series, which used the information from the calibration certificate to correct the raw data. Users can acquire sensor data values by moving the cursor over the chart.

In addition to the correction, the measurement result needs the measurement uncertainty. The yellow area represents the measurement uncertainty of the corrected data. In this case, we calculated the uncertainty by using the linearly interpolated calibration certificate associated



Welcome to VIA !

Visualise and analise sensor measurements

The Visual Information Analyzer (VIA) is an application that integrates sensor measurements with metadata, applying correction and measurements uncertainty based on the equipment calibration certificate

Access Metadata

Access main information and technical specification about the equipment

Applying Correction

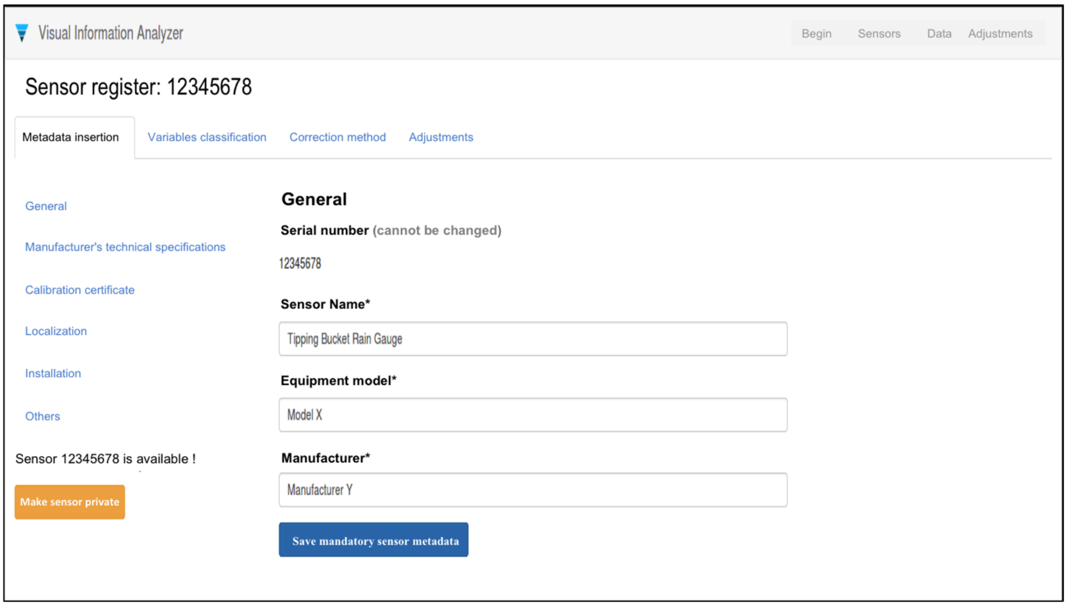
Apply corrections on the sensor

measurements based on metadata information

Visualize Uncertainty

Visualize range of uncertainty to verify measurements confiability

Fig. 6 VIA software



Sensor register: 12345678

General

Serial number (cannot be changed)

12345678

Sensor Name*: Tipping Bucket Rain Gauge

Equipment model*: Model X

Manufacturer*: Manufacturer Y

Sensor 12345678 is available !

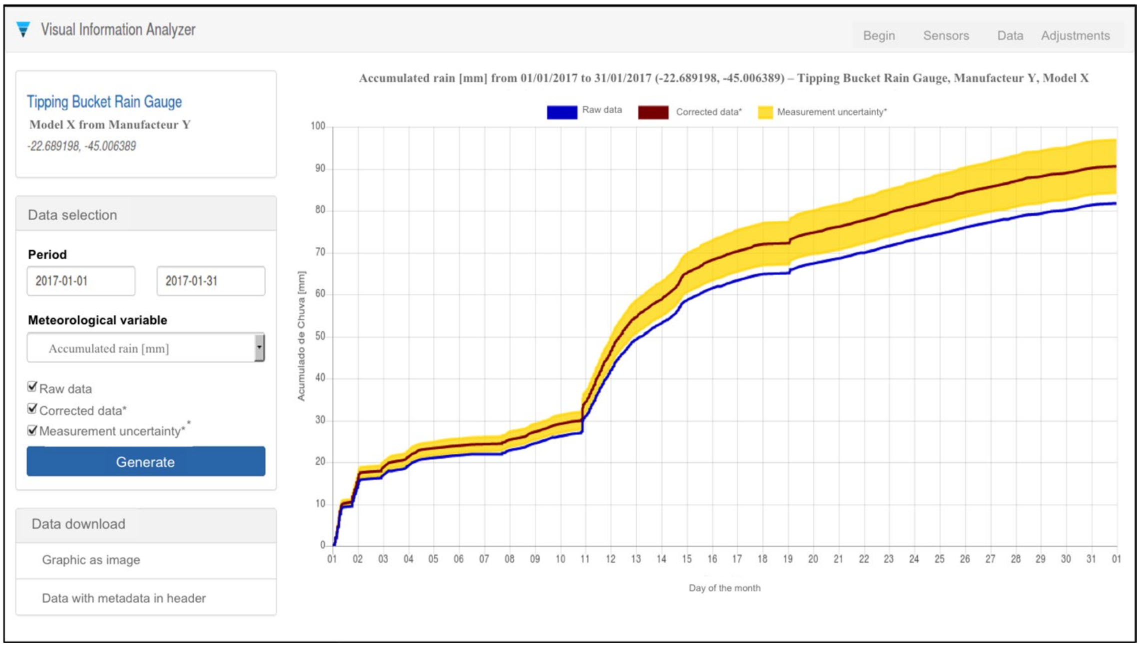
Fig. 7 Sensor metadata input interface

to the values corrected based on the rain intensity (amount of water per hour) at that minute.

The left side panel allows users to select the data through parameters related to the weather variable, time period, data series, correction and uncertainty evaluation application.

Figure 9 shows the measurement results, exported using VIA. These results are expressed according to the metrology guidelines.

Users can download the raw data, metadata and new metrological data generated by the system accordingly, using the parameters configured by the user in the data selection. The graphics can also be downloaded using an image file format.



Tipping Bucket Rain Gauge

Model X from Manufacteur Y

-22.689198, -45.006389

Period

2017-01-01

2017-01-31

Meteorological variable

Accumulated rain [mm]

☑ Raw data

☑ Corrected data*

☑ Measurement uncertainty*

Accumulated rain [mm] from 01/01/2017 to 31/01/2017 (-22.689198, -45.006389) – Tipping Bucket Rain Gauge, Manufacteur Y, Model X

Fig. 8 Sensor data: raw, corrected and measurement uncertainty

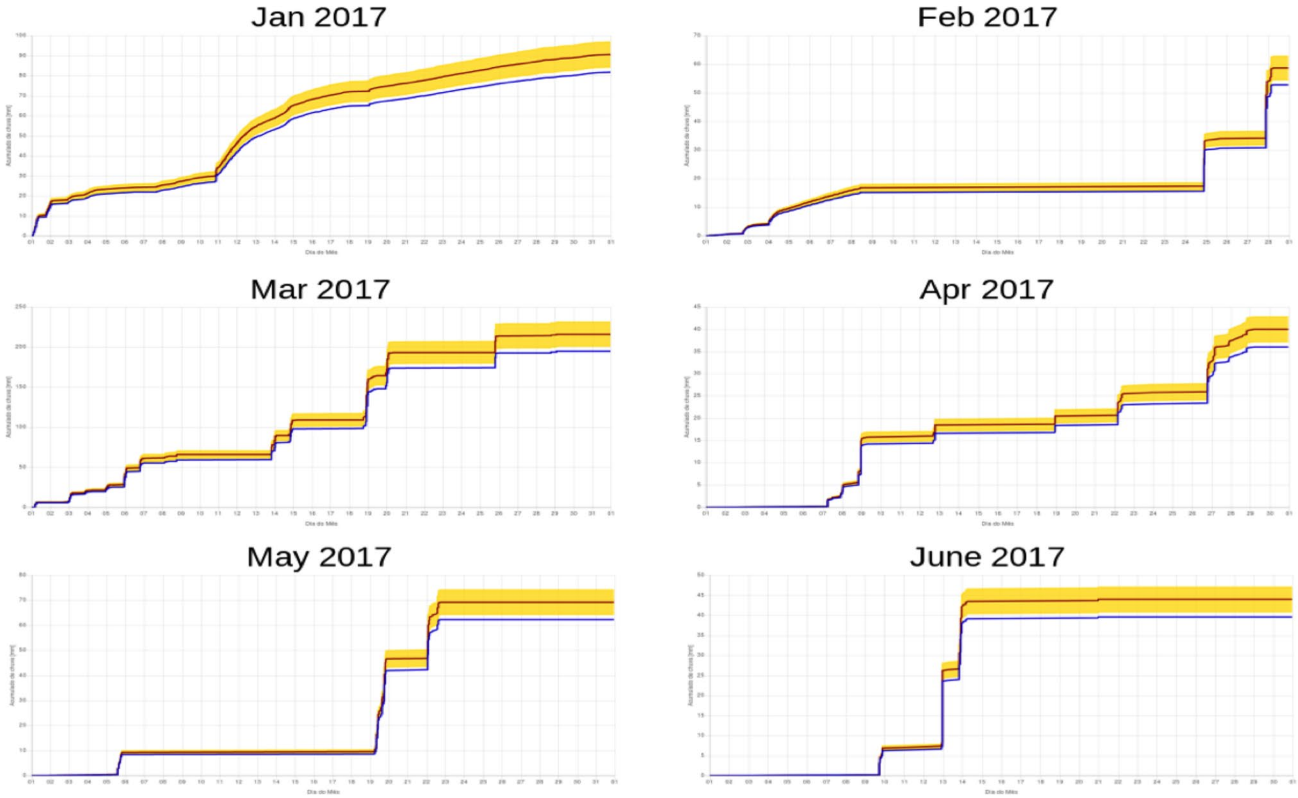


Fig. 9 Rainfall measurement result graphs exported by VIA

The ELK infrastructure was updated to deal with NetFlow data from the main switch of a meteorological datacenter, which received a maximum of ~ 470 flows/s (40,602,491 network flows in 1 day). For the amount of data used (13 Bytes/s), a single node deployment should be enough.

7 Conclusions

Systems for managing environmental sensor metadata for data treatment are still scarce. In this paper we have proposed and developed a framework to allow integration and processing of sensor data and its associated metadata for rainfall monitoring.

We have developed the Visual Information Analyzer (VIA) software to include important information for environmental data analysis, such as equipment specifications and general metrological information. It also has features to visualize raw, corrected and uncertainty of sensor data.

Our approach allows the collection of important information about sensors and its manipulation. It uses environmental metrology techniques to increase the quality of measurements, decrease errors and evaluate measurements uncertainty.

We have used an Elastic Stack based infrastructure and developed a workflow to collect, transform and store sensor data and metadata. This workflow corrects raw sensor data using its metadata, and includes the uncertainty evaluation.

The validation of the framework used precipitation data from a TBRG. A consistent and continuous flow of data and metadata, from data collection to the publication to the end user, must be maintained to increase the quality of data products related to weather and climate.

This solution can minimize the difficulties of sensor data treatment. The visualization of the sensor data, processed using metrological metadata improves data analysis.

Since each entry is associated with a timestamp, we understand that Time Series DBMS are more adequate for handling time series data. So, we are evaluating the use of Grafana[5] with Influxdb[6] instead of Elastic Stack. It has a simplified environment that allows easier deployments.

We also would like to have a version that contemplates from calibration to the complete measurement uncertainty assessment of a meteorological variable dealing with all metadata of each step. It should include statistical analysis and treatment according to metrological requirements and meteorological recommendations.

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Compliance with ethical standards

Conflict of interest On behalf of all the authors, the author declares that they have no conflict of interest.

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