A Standard for Exchangeable Magnetotelluric Metadata

Working Group for Data Handling and Software - PASSCAL Magnetotelluric Program[1]

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1 Introduction

Researchers using magnetotelluric (MT) methods lack a standardized format for storing time series data and metadata. Commercially available MT instruments produce data in formats that range from proprietary binary to ASCII, whereas recent datasets from the U.S. MT community have utilized institutional formats or heavily adapted formats like miniSEED. In many cases, the available metadata for MT time series are incomplete and loosely standardized; and overall, these datasets are not "user friendly". This lack of a standardized resource impedes the exchange and broader use of these data beyond a small community of specialists.

The IRIS PASSCAL MT facility maintains a pool of MT instruments that are freely available to U.S. Principal Investigators (PIs). Datasets collected with these instruments are subject to data sharing requirements, and an IRIS working group advises the development of sustainable data formats and workflows for this facility. Following in the spirit of the standard created for MT transfer function datasets, this document outlines a new metadata standard for level 0,1,and 2 MT time series data (Data Levels). Following community approval of these standards, MTH5 (an HDF5 MT specific format) will be developed later in 2020.

The Python 3 module written for these standards and MTH5 is being developed at `https://github.com/kujaku11/MTarchive/tree/tables`.

2 General Structure

The metadata for a full MT dataset are structured to cover details from single channel time series to a full survey. For simplicity, each of the different scales of an MT survey and measurements have been categorized starting from largest to smallest (Figure 1). These categories are: `Survey`, `Station`, `Run`, `DataLogger`, `Electric Channel`, `Magnetic Channel`, and `Auxiliary Channel`. Each category is described in subsequent sections. Required keywords are labeled as **True** and suggested keywords are labeled as **False**. A user should use as much of the suggested metadata as possible for a full description of the data.

2.1 Metadata Keyword Format

The metadata key names should be self-explanatory and are structured as follows:
`{category}.{name}`, or can be nested `{category1}.{categroy2}.{name}` where:

- `category` refers to a metadata category or level that has common parameters, such as `location`, which will have a latitude, longitude, and elevation $\longrightarrow$ `location.latitude`, `location.longitude`, and `location.elevation`. These can be nested, for example, `station.location.latitude`
- `name` is a descriptive name, where words should be separated by an underscore. Note that only whole words should be used and abbreviations should be avoided, e.g. `data_quality`.

A '.' represents the separator between different categories. The metadata can be stored in many different forms. Common forms are XML or JSON formats. See examples below for various ways to represent the metadata.

2.2 Formatting Standards

Specific and required formatting standards for location, time and date, and angles are defined below and should be adhered to.

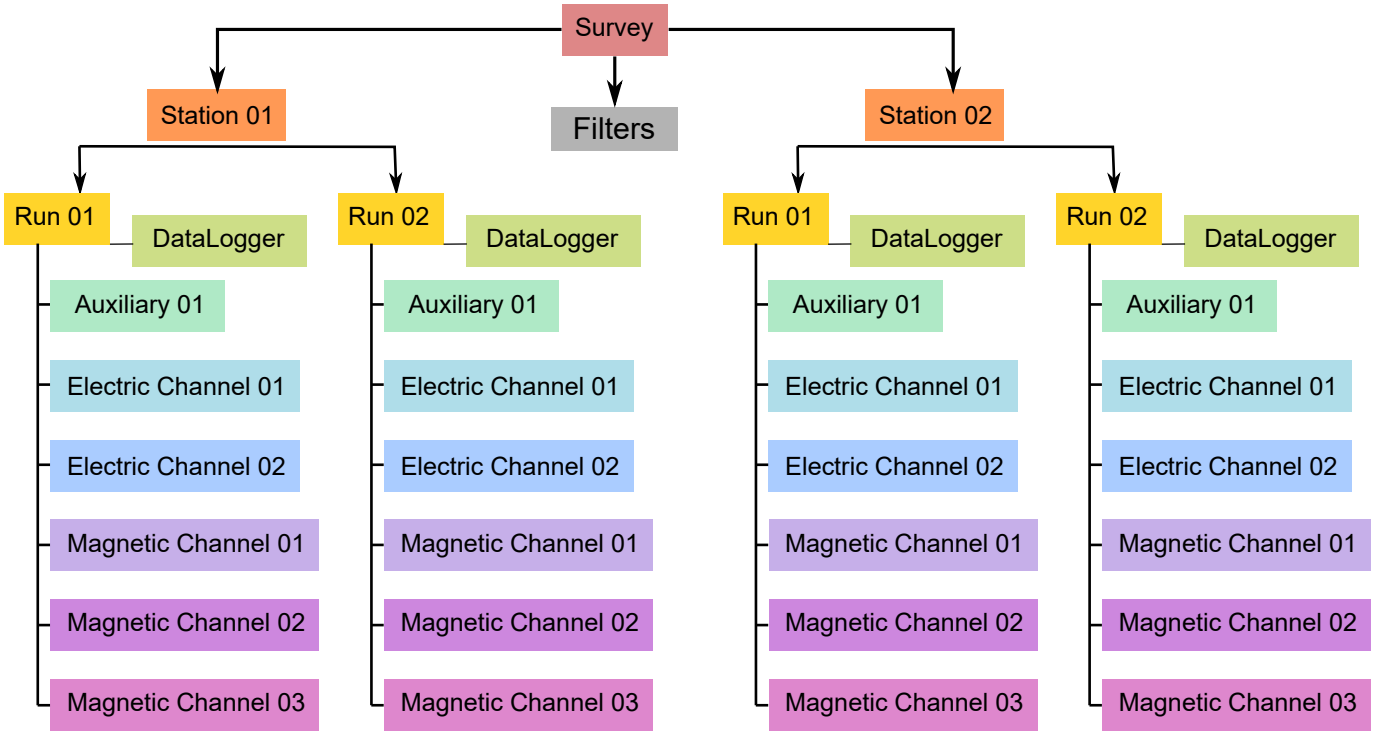

Figure 1: Schematic of a MT time series file structure with appropriate metadata. The top level is the *Survey* that contains general information about who, what, when, where, and how the data were collected. Underneath *Survey* are the *Station* and *Filter*. *Filter* contains information about different filters that need to be applied to the raw data to get appropriate units and calibrated measurements. Underneath *Station* are *Run*, which contain data that were collected at a single sampling rate with common start and end time at a single station. Finally, *Channel* describes each channel of data collected and can be an *Auxiliary*, *Electric*, or *Magnetic*. Metadata is attributed based on the type of data collected in the channel.

2.2.1 Time and Date Format

All time and dates are given as an ISO formatted date-time String in the UTC time zone. The ISO Date Time format is `YYYY-MM-DDThh:mm:ss.ms+00:00`, where the UTC time zone is represented by `+00:00`. UTC can also be denoted by `Z` at the end of the date-time string `YYYY-MM-DDThh:mm:ss.msZ`. Note that `Z` can also represent Greenwich Mean Time (GMT) but is an acceptable representation of UTC time. If the data requires a different time zone, this can be accommodated but it is recommended that UTC be used whenever possible to avoid confusion of local time and local daylight savings. Milliseconds can be accurate to 9 decimal places. ISO dates are formatted `YYYY-MM-DD`. Hours are given as a 24 hour number or military time, e.g. 4:00 PM is 16:00.

2.2.2 Location

All latitude and longitude locations are given in decimal degrees in the well known datum specified at the `Survey` level. **NOTE: The entire survey should use only one datum that is specified at the Survey level.**

- All latitude values must be $< |90|$ and all longitude values must be $< |180|$.
- Elevation and other distance values are given in meters.
- Datum should be one of the well known datums, WGS84 is preferred, but others are acceptable.

2.2.3 Angles

All angles of orientation are given in decimal degrees. Orientation of channels should be given in a geographic or a geomagnetic reference frame where the right-hand coordinates are assumed to be North = 0, East = 90, and vertical is positive downward (Figure 2). The coordinate reference frame is given at the station level `station.orientation.reference_frame`. Two angles to describe the orientation of a sensor is given by `channel.measurement_azimuth` and `channel.measurement_tilt`. In a geographic or geomagnetic reference frame, the azimuth refers to the horizontal angle relative to north positive clockwise, and the tilt refers to the vertical angle with respect to the horizontal plane. In this reference frame, a tilt angle of 90 points downward, 0 is parallel with the surface, and -90 points upwards.

Archived data should remain in measurement coordinates. Any transformation of coordinates for derived products can store the transformation angles at the channel level in `channel.transformed_azimuth` and `channel.transformed_tilt`, the transformed reference frame can then be recorded in `station.orientation.transformed_reference_frame`.

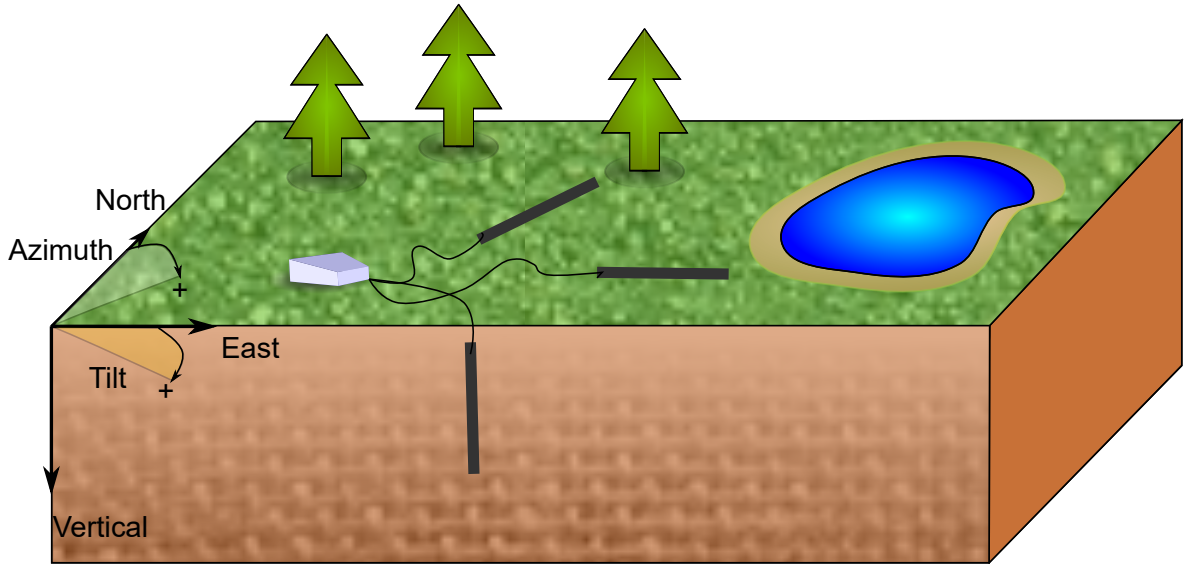

Figure 2: Diagram showing a right-handed geographic coordinate system. The azimuth is measured positive clockwise along the horizontal axis and tilt is measured from the vertical axis with positive down = 0, positive up = 180, and horizontal = 90.

2.3 Units

Acceptable units are only those from the International System of Units (SI). Only long names in all lower case are acceptable. Table 1 summarizes common acceptable units.

2.4 String Formats

Each metadata keyword can have a specific string style, such as date and time or alpha-numeric. These are described in Table 2. Note that any list should be comma separated.

Table 1: Acceptable Units

Measurement Type	Unit Name
Angles	decimal degrees
Distance	meter
Electric Field	millivolt
Latitude/Longitude	decimal degrees
Magnetic Field	nanotesla
Resistance	ohms
Resistivity	ohm-meter
Temperature	celsius
Time	second
Voltage	volt

Table 2: Acceptable String Formats

Style	Description	Example
Free Form	An unregulated string that can contain {a-z, A-Z, 0-9} and special characters	This is Free Form!
Alpha Numeric	A string that contains no spaces and only characters {a-z, A-Z, 0-9, -, /, _}	WGS84 or GEOMAG-USGS
Controlled Vocabulary	Only certain names or words are allowed. In this case, examples of acceptable values are provided in the documentation as [option01 | option02 | ...]. The ... indicates that other options are possible but have not been defined in the standards yet	reference_frame = geographic
List	List of entries using a comma separator	Ex, Ey, Hx, Hy, Hz, T
Number	A number according to the data type; number of decimal places has not been implemented yet	10.0 (float) or 10 (integer)
Date	ISO formatted date YYYY-MM-DD in UTC	2020-02-02
Date Time	ISO formatted date time YYYY-MM-DDThh:mm:ss.ms+00:00 in UTC	2020-02-02T12:20:45.123456+00:00
Email	A valid email address	person@mt.org
URL	A full URL that a user can view in a web browser	https://www.passcal.nmt.edu/

3 Survey

A survey describes an entire data set that covers a specific time span and region. This may include multiple PIs in multiple data collection episodes but should be confined to a specific experiment or project. The `Survey` metadata category describes the general parameters of the survey.

Table 3: Attributes for Survey

Metadata Key	Description	Example
acquired_by.author Required: **True** Units: None Type: String Style: Free Form	Name of the person or persons who acquired the data. This can be different from the project lead if a contractor or different group collected the data.	person name
acquired_by.comments Required: **False** Units: None Type: String Style: Free Form	Any comments about aspects of how the data were collected or any inconsistencies in the data.	Lightning strike caused a time skip at 8 am UTC.
archive_id Required: **True** Units: None Type: String Style: Alpha Numeric	Alphanumeric name provided by the archive. For IRIS this will be the FDSN providing a code.	YKN20
archive_network Required: **True** Units: None Type: String Style: Alpha Numeric	Network code given by PASSCAL/IRIS/FDSN. This will be a two character String that describes who and where the network operates.	EM
citation_dataset.doi Required: **True** Units: None Type: String Style: URL	The full URL of the doi Number provided by the archive that describes the raw data	`http://doi.10.adfabe`
citation_journal.doi Required: **False** Units: None Type: String Style: URL	The full URL of the doi Number for a journal article(s) that uses these data. If multiple journal articles use these data provide as a comma separated String of urls.	`http://doi.10.xbsfs`, or `http://doi.10.xbsfs`, `http://doi.10.xbsfs2`

Attributes for Survey Continued

Metadata Key	Description	Example
comments Required: **False** Units: None Type: String Style: Free Form	Any comments about the survey that are important for any user to know.	Solar activity low.
country Required: **True** Units: None Type: String Style: Free Form	Country or countries that the survey is located in. If multiple input as comma separated names.	USA, Canada
datum Required: **True** Units: None Type: String Style: Controlled Vocabulary	The reference datum for all geographic coordinates throughout the survey. It is up to the user to be sure that all coordinates are projected into this datum. Should be a well-known datum: [WGS84 | NAD83 | OSGB36 | GDA94 | ETRS89 | PZ-90.11 | ...]	WGS84
geographic_name Required: **True** Units: None Type: String Style: Free Form	Geographic names that encompass the survey. These should be broad geographic names. Further information can be found at https://www.usgs.gov/core-science-systems/ngp/board-on-geographic-names	Eastern Mojave, Southwestern USA
name Required: **True** Units: None Type: String Style: Free Form	Descriptive name of the survey, similar to the title of a journal article.	MT Characterization of Yukon Terrane
northwest_corner.latitude Required: **True** Units: decimal degrees Type: Float Style: Number	Latitude of the northwest corner of the survey in the datum specified.	23.134
northwest_corner.longitude Required: **True** Units: decimal degrees Type: Float Style: Number	Longitude of the northwest corner of the survey in the datum specified.	14.23

Attributes for Survey Continued

Metadata Key	Description	Example
project Required: True Units: None Type: String Style: Free Form	Alphanumeric name for the project. This is different than the archive_id in that it describes a project as having a common project lead and source of funding. There may be multiple surveys within a project. For example if the project is to estimate geomagnetic hazards that project = GEOMAG but the archive_id = YKN20.	GEOMAG
project_lead.author Required: True Units: None Type: String Style: Free Form	Name of the project lead. This should be a person who is responsible for the data.	Magneto
project_lead.email Required: True Units: None Type: String Style: Email	Email of the project lead. This is in case there are any questions about data.	mt.guru@em.org
project_lead.organization Required: True Units: None Type: String Style: Free Form	Organization name of the project lead.	MT Gurus
release_license Required: True Units: None Type: String Style: Controlled Vocabulary	How the data can be used. The options are based on Creative Commons licenses. Options: [CC 0 | CC BY | CC BY-SA| CC BY-ND | CC BY-NC-SA | CC BY-NC-ND]. For details visit https://creativecommons.org/licenses/	CC 0
southeast_corner.latitude Required: True Units: decimal degrees Type: Float Style: Number	Latitude of the southeast corner of the survey in the datum specified.	23.134
southeast_corner.longitude Required: True Units: decimal degrees Type: Float Style: Number	Longitude of the southeast corner of the survey in the datum specified.	14.23

Attributes for Survey Continued

Metadata Key	Description	Example
summary Required: **True** Units: None Type: String Style: Free Form	Summary paragraph of the survey including the purpose; difficulties; data quality; summary of outcomes if the data have been processed and modeled.	Long project of characterizing mineral resources in Yukon
time_period.end_date Required: **True** Units: None Type: String Style: Date	End date of the survey in UTC.	2020-02-01
time_period.start_date Required: **True** Units: None Type: String Style: Date	Start date of the survey in UTC.	1995-06-21

3.1 Example Survey XML Element

```
<?xml version="1.0" ?>
<survey>
    <acquired_by>
        <author>MT Graduate Students</author>
        <comments>Multiple over 5 years</comments>
    </acquired_by>
    <archive_id>SAM1990</archive_id>
    <archive_network>EM</archive_network>
    <citation_dataset>
        <doi>https://doi.###</doi>
    </citation_dataset>
    <citation_journal>
        <doi>https://doi.###</doi>
    </citation_journal>
    <comments>None</comments>
    <country>USA, Canada</country>
    <datum>WGS84</datum>
    <geographic_name>Yukon</geographic_name>
    <name>Imaging Gold Deposits of the Yukon Province</name>
    <northwest_corner>
        <latitude type="Float" units="decimal degrees">-130</latitude>
        <longitude type="Float" units="decimal degrees">75.9</longitude>
    </northwest_corner>
    <project>AURORA</project>
    <project_lead>
        <Email>m.tee@mt.org</Email>
        <organization>EM Ltd.</organization>
        <author>M. Tee</author>
    </project_lead>
    <release_license>CC0</release_license>
    <southeast_corner>
        <latitude type="Float" units="decimal degrees">-110.0</latitude>
        <longitude type="Float" units="decimal degrees">65.12</longitude>
    </southeast_corner>
    <summary>This survey spanned multiple years with graduate students
             collecting the data.  Lots of curious bears and moose,
             some interesting signal from the aurora.  Modeled data
             image large scale crustal features like the
             "fingers of god" that suggest large mineral deposits.
    </summary>
    <time_period>
        <end_date>2020-01-01</end_date>
        <start_date>1995-01-01</start_date>
    </time_period>
</survey>
```

4 Station

A station encompasses a single site where data are collected. If the location changes during a run, then a new station should be created and subsequently a new run under the new station. If the sensors, cables, data logger, battery, etc. are replaced during a run but the station remains in the same location, then this can be recorded in the `Run` metadata but does not require a new station entry.

Table 4: Attributes for Station

Metadata Key	Description	Example
acquired_by.author Required: True Units: None Type: String Style: Free Form	Name of person or group that collected the station data and will be the point of contact if any questions arise about the data.	person name
acquired_by.comments Required: False Units: None Type: String Style: Free Form	Any comments about who acquired the data.	Expert diggers.
archive_id Required: True Units: None Type: String Style: Alpha Numeric	Station name that is archived a-z;A-Z;0-9. For IRIS this is a 5 character String.	MT201
channel_layout Required: False Units: None Type: String Style: Controlled Vocabulary	How the dipoles and magnetic channels of the station were laid out. Options: [L | + | ...]	+
channels_recorded Required: True Units: None Type: String Style: Controlled Vocabulary	List of components recorded by the station. Should be a summary of all channels recorded dropped channels will be recorded in Run. Options: [Ex | Ey | Hx | Hy | Hz | T | Battery | ...]	Ex, Ey, Hx, Hy, Hz, T
comments Required: False Units: None Type: String Style: Free Form	Any comments on the station that would be important for a user.	Pipeline near by.

Attributes for Station Continued

Metadata Key	Description	Example
data_type Required: **True** Units: None Type: String Style: Controlled Vocabulary	All types of data recorded by the station. If multiple types input as a comma separated list. Options: [RMT | AMT | BBMT | LPMT | ULPMT | ...]	BBMT
geographic_name Required: **True** Units: None Type: String Style: Free Form	Closest geographic name to the station, should be rather general. For further details about geographic names see https://www.usgs.gov/core-science-systems/ngp/board-on-geographic-names	"Whitehorse, YK"
id Required: **True** Units: None Type: String Style: Free Form	Station name. This can be a longer name than the archive_id name and be a more explanatory name.	bear hallabaloo
location.declination.comments Required: **False** Units: None Type: String Style: Free Form	Any comments on declination that are important to an end user.	Different than recorded declination from data logger.
location.declination.model Required: **True** Units: None Type: String Style: Controlled Vocabulary	Name of the geomagnetic reference model as {model_name}{-}{YYYY}. Model options: [EMAG2 | EMM | HDGM | IGRF | WMM]	WMM-2016
location.declination.value Required: **True** Units: decimal degrees Type: Float Style: Number	Declination angle relative to geographic north positive clockwise estimated from location and geomagnetic model.	12.3
location.elevation Required: **True** Units: meters Type: Float Style: Number	Elevation of station location in datum specified at survey level.	123.4

Attributes for Station Continued

Metadata Key	Description	Example
location.latitude Required: **True** Units: decimal degrees Type: Float Style: Number	Latitude of station location in datum specified at survey level.	23.134
location.longitude Required: **True** Units: decimal degrees Type: Float Style: Number	Longitude of station location in datum specified at survey level.	14.23
orientation.method Required: **True** Units: None Type: String Style: Controlled Vocabulary	Method for orienting station channels. Options: [compass | GPS | theodolite | electric_compass | ...]	compass
orientation.reference_frame Required: **True** Units: None Type: String Style: Controlled Vocabulary	Reference frame for station layout. There are only 2 options geographic and geomagnetic. Both assume a right-handed coordinate system with North=0, E=90 and vertical positive downward. Options: [geographic | geomagnetic]	geomagnetic
orientation.transformed_reference_frame Required: **False** Units: None Type: Float Style: Number	Reference frame rotation angel relative to orientation.reference_frame assuming positive clockwise. Should only be used if data are rotated.	10
provenance.comments Required: **False** Units: None Type: String Style: Free Form	Any comments on provenance of the data.	From a graduated graduate student.
provenance.creation_time Required: **True** Units: None Type: String Style: Date Time	Date and time the file was created.	2020-02-08 T12:23:40.324600 +00:00

Attributes for Station Continued

Metadata Key	Description	Example
provenance.log Required: **False** Units: None Type: String Style: Free Form	A history of any changes made to the data.	2020-02-10 T14:24:45+00:00 updated station metadata.
provenance.software.author Required: **True** Units: None Type: String Style: Free Form	Author of the software used to create the data files.	programmer 01
provenance.software.name Required: **True** Units: None Type: String Style: Free Form	Name of the software used to create data files	mtrules
provenance.software.version Required: **True** Units: None Type: String Style: Free Form	Version of the software used to create data files	12.01a
provenance.submitter.author Required: **True** Units: None Type: String Style: Free Form	Name of the person submitting the data to the archive.	person name
provenance.submitter.email Required: **True** Units: None Type: String Style: Email	Email of the person submitting the data to the archive.	mt.guru@em.org
provenance.submitter.organization Required: **True** Units: None Type: String Style: Free Form	Name of the organization that is submitting data to the archive.	MT Gurus

Attributes for Station Continued

Metadata Key	Description	Example
time_period.end Required: **True** Units: None Type: String Style: Date Time	End date and time of collection in UTC.	2020-02-04 T16:23:45.453670 +00:00
time_period.start Required: **True** Units: None Type: String Style: Date Time	Start date and time of collection in UTC.	2020-02-01 T09:23:45.453670 +00:00

4.1 Example Station JSON


```
{    "station": {
        "acquired_by": {
            "author": "mt",
            "comments": null},
        "archive_id": "MT012",
        "channel_layout": "L",
        "channels_recorded": "Ex, Ey, Hx, Hy",
        "comments": null,
        "data_type": "MT",
        "geographic_name": "Whitehorse, Yukon",
        "id": "Curious Bears Hallabaloo",
        "location": {
            "latitude": 10.0,
            "longitude": -112.98,
            "elevation": 1234.0,
            "declination": {
                "value": 12.3,
                "comments": null,
                "model": "WMM-2016"}},
        "orientation": {
            "method": "compass",
            "reference_frame": "geomagnetic"},
        "provenance": {
            "comments": null,
            "creation_time": "1980-01-01T00:00:00+00:00",
            "log": null,
            "software": {
                "author": "test",
                "version": "1.0a",
                "name": "name"},
            "submitter": {
                "author": "name",
                "organization": null,
                "email": "test@here.org"}},
        "time_period": {
            "end": "1980-01-01T00:00:00+00:00",
            "start": "1982-01-01T16:45:15+00:00"}
         }
}
```

5 Run

A run represents data collected at a single station with a single sampling rate. If the dipole length or other such station parameters are changed between runs, this would require adding a new run. If the station is relocated then a new station should be created. If a run has channels that drop out, the start and end period will be the minimum time and maximum time for all channels recorded.

Table 5: Attributes for Run

Metadata Key	Description	Example
acquired_by.author Required: True Units: None Type: String Style: Free Form	Name of the person or persons who acquired the run data. This can be different from the station.acquired_by and survey.acquired_by.	M.T. Nubee
acquired_by.comments Required: False Units: None Type: String Style: Free Form	Any comments about who acquired the data.	Group of undergraduates.
channels_recorded_auxiliary Required: True Units: None Type: String Style: name list	List of auxiliary channels recorded.	T, battery
channels_recorded_electric Required: True Units: None Type: String Style: name list	List of electric channels recorded.	Ex, Ey
channels_recorded_magnetic Required: True Units: None Type: String Style: name list	List of magnetic channels recorded.	Hx, Hy, Hz
comments Required: False Units: None Type: String Style: Free Form	Any comments on the run that would be important for a user.	Badger attacked Ex.

Attributes for Run Continued

Metadata Key	Description	Example
comments Required: **False** Units: None Type: String Style: Free Form	Any comments on the run that would be important for a user.	cows chewed cables at 9am local time.
data_logger.firmware.author Required: **True** Units: None Type: String Style: Free Form	Author of the firmware that runs the data logger.	instrument engineer
data_logger.firmware.name Required: **False** Units: None Type: String Style: Free Form	Name of the firmware the data logger runs.	mtrules
data_logger.firmware.version Required: **False** Units: None Type: String Style: Free Form	Version of the firmware that runs the data logger.	12.01a
data_logger.id Required: **False** Units: None Type: String Style: Free Form	Instrument ID Number can be serial Number or a designated ID.	mt01
data_logger.manufacturer Required: **True** Units: None Type: String Style: Free Form	Name of person or company that manufactured the data logger.	MT Gurus
data_logger.model Required: **True** Units: None Type: String Style: Free Form	Model version of the data logger.	falcon5

Attributes for Run Continued

Metadata Key	Description	Example
data_logger.power_source.comments Required: **False** Units: None Type: String Style: Name	Any comment about the power source.	Used a solar panel and it was cloudy.
data_logger.power_source.id Required: **False** Units: None Type: String Style: name	Battery ID or name	battery01
data_logger.power_source.type Required: **False** Units: None Type: String Style: name	Battery type	pb-acid gel cell
data_logger.power_source.voltage.end Required: **False** Units: volts Type: Float Style: Number	End voltage	12.1
data_logger.power_source.voltage.start Required: **False** Units: volts Type: Float Style: Number	Starting voltage	14.3
data_logger.timing_system.comments Required: **False** Units: None Type: String Style: Free Form	Any comment on timing system that might be useful for the user.	GPS locked with internal quartz clock
data_logger.timing_system.drift Required: **False** Units: seconds Type: Float Style: Number	Estimated drift of the timing system.	0.001

Attributes for Run Continued

Metadata Key	Description	Example
data_logger.timing_system.type Required: **False** Units: None Type: String Style: Free Form	Type of timing system used in the data logger.	GPS
data_logger.timing_system.uncertainty Required: **False** Units: seconds Type: Float Style: Number	Estimated uncertainty of the timing system.	0.0002
data_logger.type Required: **True** Units: None Type: String Style: Free Form	Type of data logger, this should specify the bit rate and any other parameters of the data logger.	broadband 32-bit
data_type Required: **True** Units: None Type: String Style: Controlled Vocabulary	Type of data recorded for this run. Options: [RMT | AMT | BBMT | LPMT | ULPMT | ...]	BBMT
id Required: **True** Units: None Type: String Style: Alpha Numeric	Name of the run. Should be station name followed by an alphabet letter for the run.	MT302b
metadata_by.author Required: **True** Units: None Type: String Style: Free Form	Person who input the metadata.	Metadata Zen
metadata_by.comments Required: **False** Units: None Type: String Style: Free Form	Any comments about the metadata that would be useful for the user.	Undergraduate did the input.

Attributes for Run

Metadata Key	Description	Example
provenance.comments Required: **False** Units: None Type: String Style: Free Form	Any comments on provenance of the data that would be useful to users.	all good
provenance.log Required: **False** Units: None Type: String Style: Free Form	A history of changes made to the data.	2020-02-10 T14:24:45 +00:00 updated metadata
sampling_rate Required: **True** Units: samples per second Type: Float Style: Number	Sampling rate for the recorded run.	100
time_period.end Required: **True** Units: None Type: String Style: Date Time	End date and time of collection in UTC.	2020-02-04 T16:23:45.453670 +00:00
time_period.start Required: **True** Units: None Type: String Style: Date Time	Start date and time of collection in UTC.	2020-02-01 T09:23:45.453670 +00:00

5.1 Example Run JSON


```
{
    "run": {
        "acquired_by.author": "Magneto",
        "acquired_by.comments": "No hands all telekinesis.",
        "channels_recorded_auxiliary": ["temperature", "battery"],
        "channels_recorded_electric": ["Ex", "Ey"],
        "channels_recorded_magnetic": ["Hx", "Hy", "Hz"],
        "comments": "Good solar activity",
        "data_logger.firmware.author": "Engineer 01",
        "data_logger.firmware.name": "MTDL",
        "data_logger.firmware.version": "12.23a",
        "data_logger.id": "DL01",
        "data_logger.manufacturer": "MT Gurus",
        "data_logger.model": "Falcon 7",
        "data_logger.power_source.comments": "Used solar panel but cloudy",
        "data_logger.power_source.id": "Battery_07",
        "data_logger.power_source.type": "Pb-acid gel cell 72 Amp-hr",
        "data_logger.power_source.voltage.end": 14.1,
        "data_logger.power_source.voltage.start": 13.7,
        "data_logger.timing_system.comments": null,
        "data_logger.timing_system.drift": 0.000001,
        "data_logger.timing_system.type": "GPS + internal clock",
        "data_logger.timing_system.uncertainty": 0.0000001,
        "data_logger.type": "Broadband 32-bit 5 channels",
        "data_type": "BBMT",
        "id": "YKN201b",
        "metadata_by.author": "Graduate Student",
        "metadata_by.comments": "Lazy",
        "provenance.comments": "Data found on old hard drive",
        "provenance.log": "2020-01-02 Updated metadata from old records",
        "sampling_rate": 256,
        "time_period.end": "1999-06-01T15:30:00+00:00",
        "time_period.start": "1999-06-5T20:45:00+00:00"
    }
}
```

6 Electric Channel

Electric channel refers to a dipole measurement of the electric field for a single station for a single run.

Table 6: Attributes for Electric

Metadata Key	Description	Example
ac.end Required: **False** Units: volts Type: Float Style: Number	Ending AC value; if more than one measurement input as a list of Number [1 2 ...]	45.3, 49.5
ac.start Required: **False** Units: volts Type: Float Style: Number	Starting AC value; if more than one measurement input as a list of Number [1 2 ...]	52.1, 55.8
channel_number Required: **True** Units: None Type: Integer Style: Number	Channel number on the data logger of the recorded channel.	1
comments Required: **False** Units: None Type: String Style: Free Form	Any comments about the channel that would be useful to a user.	Lightning storm at 6pm local time
component Required: **True** Units: None Type: String Style: Controlled Vocabulary	Name of the component measured. Options: [Ex | Ey | ...]	Ex
contact_resistance.end Required: **False** Units: ohms Type: Float Style: Number list	Starting contact resistance; if more than one measurement input as a list [1, 2, ...]	1.5, 1.8

Attributes for Electric Continued

Metadata Key	Description	Example
contact_resistance.start Required: **False** Units: ohms Type: Float Style: Number list	Starting contact resistance; if more than one measurement input as a list [1, 2, ...]	1.2, 1.4
data_quality.rating.author Required: **False** Units: None Type: String Style: Free Form	Name of person or organization who rated the data.	graduate student ace
data_quality.rating.method Required: **False** Units: None Type: String Style: Free Form	The method used to rate the data. Should be a descriptive name and not just the name of a software package. If a rating is provided, the method should be recorded.	standard deviation
data_quality.rating.value Required: **True** Units: None Type: Integer Style: Number	Rating from 1-5 where 1 is bad, 5 is good, and 0 is unrated. Options: [0 | 1 | 2 | 3 | 4 | 5]	4
data_quality.warning Required: **False** Units: None Type: String Style: Free Form	Any warnings about the data that should be noted for users.	periodic pipeline noise
dc.end Required: **False** Units: volts Type: Float Style: Number	Ending DC value; if more than one measurement input as a list [1, 2, ...]	1.5
dc.start Required: **False** Units: volts Type: Float Style: Number	Starting DC value; if more than one measurement input as a list [1, 2, ...]	1.1

Attributes for Electric Continued

Metadata Key	Description	Example
dipole_length Required: True Units: meters Type: Float Style: Number	Length of the dipole	55.25
filter.applied Required: True Units: None Type: Boolean Style: List	Boolean if filter has been applied or not. If more than one filter, input as a comma separated list. Needs to be the same length as filter.name. If only one entry is given, it is assumed to apply to all filters listed.	True, True
filter.comments Required: False Units: None Type: String Style: Free Form	Any comments on filters that is important for users.	low pass is not calibrated
filter.name Required: True Units: None Type: String Style: List	Name of filter applied or to be applied. If more than one filter, input as a comma separated list.	counts2mv, lowpass_electric
measurement_azimuth Required: True Units: decimal degrees Type: Float Style: Number	Azimuth angle of the channel in the specified survey.orientation.reference_frame.	0
measurement_tilt Required: True Units: decimal degrees Type: Float Style: Number	Tilt angle of channel in survey.orientation.reference_frame.	0
negative.elevation Required: True Units: meters Type: Float Style: Number	Elevation of negative electrode in datum specified at survey level.	123.4

Attributes for Electric Continued

Metadata Key	Description	Example
negative.id Required: **False** Units: None Type: String Style: Free Form	Negative electrode ID Number, can be serial number or a designated ID.	electrode01
negative.latitude Required: **False** Units: decimal degrees Type: Float Style: Number	Latitude of negative electrode in datum specified at survey level.	23.134
negative.longitude Required: **False** Units: decimal degrees Type: Float Style: Number	Longitude of negative electrode in datum specified at survey level.	14.23
negative.manufacturer Required: **False** Units: None Type: String Style: Free Form	Person or organization that manufactured the electrode.	Electro-Dudes
negative.model Required: **False** Units: None Type: String Style: Free Form	Model version of the electrode.	falcon5
negative.type Required: **True** Units: None Type: String Style: Free Form	Type of electrode, should specify the chemistry.	Ag-AgCl
positive.elevation Required: **False** Units: meters Type: Float Style: Number	Elevation of the positive electrode in datum specified at survey level.	123.4

Attributes for Electric Continued

Metadata Key	Description	Example
positive.id Required: **False** Units: None Type: String Style: Free Form	Positive electrode ID Number, can be serial Number or a designated ID.	electrode02
positive.latitude Required: **False** Units: decimal degrees Type: Float Style: Number	Latitude of positive electrode in datum specified at survey level.	23.134
positive.longitude Required: **False** Units: decimal degrees Type: Float Style: Number	Longitude of positive electrode in datum specified at survey level.	14.23
positive.manufacturer Required: **False** Units: None Type: String Style: Free Form	Name of group or person that manufactured the electrode.	Electro-Dudes
positive.model Required: **False** Units: None Type: String Style: Free Form	Model version of the electrode.	falcon5
positive.type Required: **True** Units: None Type: String Style: Free Form	Type of electrode, should include chemistry of the electrode.	Pb-PbCl
sample_rate Required: **True** Units: samples per second Type: Float Style: Number	Sample rate of the channel.	8

Attributes for Electric Continued

Metadata Key	Description	Example
time_period.end Required: **True** Units: None Type: String Style: Date Time	End date and time of collection in UTC	2020-02-04 T16:23:45.453670 +00:00
time_period.start Required: **True** Units: None Type: String Style: Date Time	Start date and time of collection in UTC.	2020-02-01T 09:23:45.453670 +00:00
transformed_azimuth Required: **False** Units: decimal degrees Type: Float Style: Number	Azimuth angle of channel that has been transformed into a specified coordinate system. Note this value is only for derivative products from the archived data.	0
transformed_tilt Required: **False** Units: decimal degrees Type: Float Style: Number	Tilt angle of channel that has been transformed into a specified coordinate system. Note this value is only for derivative products from the archived data.	0
type Required: **True** Units: None Type: String Style: Free Form	Data type for the channel.	electric
units Required: **True** Units: None Type: String Style: Controlled Vocabulary	Units of the data, if archived data should always be in counts. Options: [counts | millivolts]	counts

6.1 Example Electric Channel JSON


```
{
 "electric": {
    "ac.end": 10.2,
    "ac.start": 12.1,
    "channel_number": 2,
    "comments": null,
    "component": "EX",
    "contact_resistance.end": 1.2,
    "contact_resistance.start": 1.1,
    "data_quality.rating.author": "mt",
    "data_quality.rating.method": "ml",
    "data_quality.rating.value": 4,
    "data_quality.warning": null,
    "dc.end": 1.0,
    "dc.start": 2.0,
    "dipole_length": 100.0,
    "filter.applied": [false],
    "filter.comments": null,
    "filter.name": [ "counts2mv", "lowpass"],
    "measurement_azimuth": 90.0,
    "measurement_tilt": 20.0,
    "negative.elevation": 100.0,
    "negative.id": "a",
    "negative.latitude": 12.12,
    "negative.longitude": -111.12,
    "negative.manufacturer": "test",
    "negative.model": "fats",
    "negative.type": "pb-pbcl",
    "positive.elevation": 101.0,
    "positive.id": "b",
    "positive.latitude": 12.123,
    "positive.longitude": -111.14,
    "positive.manufacturer": "test",
    "positive.model": "fats",
    "positive.type": "ag-agcl",
    "sample_rate": 256.0,
    "time_period.end": "1980-01-01T00:00:00+00:00",
    "time_period.start": "2020-01-01T00:00:00+00:00",
    "type": "electric",
    "units": "counts"
  }
}
```

7 Magnetic Channel

A magnetic channel is a recording of one component of the magnetic field at a single station for a single run.

Table 7: Attributes for Magnetic

Metadata Key	Description	Example
channel_number Required: True Units: None Type: Integer Style: Number	Channel Number on the data logger.	1
comments Required: False Units: None Type: String Style: Free Form	Any comments about the channel that would be useful to a user.	Pc1 at 6pm local time.
component Required: True Units: None Type: String Style: Controlled Vocabulary	Name of the component measured. Options: [Hx | Hy | Hz | ...]	Hx
data_quality.rating.author Required: False Units: None Type: String Style: Free Form	Name of person or organization who rated the data.	graduate student ace
data_quality.rating.method Required: False Units: None Type: String Style: Free Form	The method used to rate the data. Should be a descriptive name and not just the name of a software package. If a rating is provided, the method should be recorded.	standard deviation
data_quality.rating.value Required: True Units: None Type: Integer Style: Number	Rating from 1-5 where 1 is bad, 5 is good, and 0 is unrated. Options: [0 | 1 | 2 | 3 | 4 | 5]	4

Attributes for Magnetic Continued

Metadata Key	Description	Example
data_quality.warning Required: **False** Units: None Type: String Style: Free Form	Any warnings about the data that should be noted for users.	periodic pipeline noise
filter.applied Required: **True** Units: None Type: Boolean Style: List	Boolean if filter has been applied or not. If more than one filter, input as a comma separated list. Needs to be the same length as filter.name. If only one entry is given, it is assumed to apply to all filters listed.	True, True
filter.comments Required: **False** Units: None Type: String Style: Free Form	Any comments on filters that is important for users.	low pass is not calibrated
filter.name Required: **True** Units: None Type: String Style: List	Name of filter applied or to be applied. If more than one filter, input as a comma separated list.	counts2mv, lowpass_electric
h_field_max.end Required: **False** Units: nanotesla Type: Float Style: Number	Maximum magnetic field strength at end of measurement.	34526.1
h_field_max.start Required: **False** Units: nanotesla Type: Float Style: Number	Maximum magnetic field strength at beginning of measurement.	34565.2
h_field_min.end Required: **False** Units: nanotesla Type: Float Style: Number	Minimum magnetic field strength at end of measurement.	50453.2

Attributes for Magnetic Continued

Metadata Key	Description	Example
h_field_min.start Required: **False** Units: nt Type: Float Style: Number	Minimum magnetic field strength at beginning of measurement.	40345.1
location.elevation Required: **False** Units: meters Type: Float Style: Number	elevation of magnetometer in datum specified at survey level.	123.4
location.latitude Required: **False** Units: decimal degrees Type: Float Style: Number	Latitude of magnetometer in datum specified at survey level.	23.134
location.longitude Required: **False** Units: decimal degrees Type: Float Style: Number	Longitude of magnetometer in datum specified at survey level.	14.23
measurement_azimuth Required: **True** Units: decimal degrees Type: Float Style: Number	Azimuth of channel in the specified survey.orientation.reference_frame.	0
measurement_tilt Required: **True** Units: decimal degrees Type: Float Style: Number	Tilt of channel in survey.orientation.reference_frame.	0
sample_rate Required: **True** Units: samples per second Type: Float Style: Number	Sample rate of the channel.	8

Attributes for Magnetic Continued

Metadata Key	Description	Example
sensor.id Required: **False** Units: None Type: String Style: Free Form	Sensor ID Number or serial Number.	mag01
sensor.manufacturer Required: **False** Units: None Type: String Style: Free Form	Person or organization that manufactured the magnetic sensor.	Magnets
sensor.model Required: **False** Units: None Type: String Style: Free Form	Model version of the magnetic sensor.	falcon5
sensor.type Required: **True** Units: None Type: String Style: Free Form	Type of magnetic sensor, should describe the type of magnetic field measurement.	induction coil
time_period.end Required: **True** Units: None Type: String Style: Date Time	End date and time of collection in UTC.	2020-02-04 T16:23:45.453670 +00:00
time_period.start Required: **True** Units: None Type: String Style: Date Time	Start date and time of collection in UTC.	2020-02-01 T09:23:45.453670 +00:00
transformed_azimuth Required: **False** Units: decimal degrees Type: Float Style: Number	Azimuth angle of channel that has been transformed into a specified coordinate system. Note this value is only for derivative products from the archived data.	0

Attributes for Magnetic Continued

Metadata Key	Description	Example
transformed_tilt Required: **False** Units: decimal degrees Type: Float Style: Number	Tilt angle of channel that has been transformed into a specified coordinate system. Note this value is only for derivative products from the archived data.	0
type Required: **True** Units: None Type: String Style: Free Form	Data type for the channel	magnetic
units Required: **True** Units: None Type: String Style: Controlled Vocabulary	Units of the data. if archiving should always be counts. Options: [counts | nanotesla]	counts

7.1 Example Magnetic Channel JSON


```
{    "magnetic": {
        "comments": null,
        "component": "Hz",
        "data_logger": {
            "channel_number": 2},
        "data_quality": {
            "warning": "periodic pipeline",
            "rating": {
                "author": "M. Tee",
                "method": "Machine Learning",
                "value": 3}},
        "filter": {
            "name": ["counts2nT", "lowpass_mag"],
            "applied": [true, false],
            "comments": null},
        "h_field_max": {
            "start": 40000.,
            "end": 420000.},
        "h_field_min": {
            "start": 38000.,
            "end": 39500.},
        "location": {
            "latitude": 25.89,
            "longitude": -110.98,
            "elevation": 1234.5},
        "measurement_azimuth": 0.0,
        "measurement_tilt": 180.0,
        "sample_rate": 64.0,
        "sensor": {
            "id": 'spud',
            "manufacturer": "F. McAraday",
            "type": "tri-axial fluxgate",
            "model": "top hat"},
        "time_period": {
            "end": "2010-01-01T00:00:00+00:00",
            "start": "2020-01-01T00:00:00+00:00"},
        "type": "magnetic",
        "units": "nT"
    }
}
```

8 Filters

`Filters` is a table that holds information on any filters that need to be applied to get physical units, and/or filters that were applied to the data to analyze the signal. This includes calibrations, notch filters, conversion of counts to units, etc. The actual filter will be an array of numbers contained within an array named `name` and formatted according to `type`. The preferred format for a filter is a look-up table which programatically can be converted to other formats.

It is important to note that filters will be identified by name and must be consistent throughout the file. Names should be descriptive and self evident. Examples:

- `coil_2284` $\longrightarrow$ induction coil Number 2284
- `counts2mv` $\longrightarrow$ conversion from counts to mV
- `e_gain` $\longrightarrow$ electric field gain
- `datalogger_response_024` $\longrightarrow$ data logger Number 24 response
- `notch_60hz` $\longrightarrow$ notch filter for 60 Hz and harmonics
- `lowpass_10hz` $\longrightarrow$ low pass filter below 10 Hz

In each channel there are keys to identify filters that can or have been applied to the data to get an appropriate signal. This can be a list of filter names or a single filter name. An `applied` key also exists for the user to input whether that filter has been applied. A single Boolean can be provided `True` if all filters have been applied, or `False` if none of the filters have been applied. Or `applied` can be a list the same length as `names` identifying if the filter has been applied. For example `name: "[counts2mv, notch_60hz, e_gain]"` and `applied: "[True, False, True]` would indicate that `counts2mv` and `e_gain` have been applied but `noth_60hz` has not.

8.1 Example Filter JSON

```
{
    "filter":{
        "type": "look up",
         "name": "counts2mv",
         "units_in": "counts",
         "units_out": "mV",
         "calibration_date": "2015-07-01",
        "comments": "Accurate to 0.001 mV"
    }
}
```

Table 8: Attributes for Filter

Metadata Key	Description	Example
type Required: **True** Units: None Type: String Style: Controlled Vocabulary	Filter type. Options: [look up | poles zeros | converter | FIR | ...]	lookup
name Required: **True** Units: None Type: String Style: Alpha Numeric	Unique name for the filter such that it is easy to query. See above for some examples.	counts2mv
units_in Required: **True** Units: None Type: String Style: Controlled Vocabulary	The input units for the filter. Should be SI units or counts.	counts
units_out Required: **True** Units: None Type: String Style: Controlled Vocabulary	The output units for the filter. Should be SI units or counts.	millivolts
calibration_date Required: **True** Units: None Type: String Style: Date Time	If the filter is a calibration, include the calibration date.	2010-01-01 T00:00:00 +00:00

9 Auxiliary Channels

Auxiliary channels include state of health channels, temperature, etc.

Table 9: Attributes for Auxiliary

Metadata Key	Description	Example
channel_number Required: True Units: None Type: Integer Style: Number	Channel Number on the data logger.	1
comments Required: False Units: None Type: String Style: Free Form	Any comments about the channel that would be useful to a user.	Pc1 at 6pm local time.
component Required: True Units: None Type: String Style: Controlled Vocabulary	Name of the component measured. Options: [temperature | battery | ...]	temperature
data_quality.rating.author Required: False Units: None Type: String Style: Free Form	Name of person or organization who rated the data.	graduate student ace
data_quality.rating.method Required: False Units: None Type: String Style: Free Form	The method used to rate the data. Should be a descriptive name and not just the name of a software package. If a rating is provided, the method should be recorded.	standard deviation
data_quality.rating.value Required: True Units: None Type: Integer Style: Number	Rating from 1-5 where 1 is bad, 5 is good, and 0 is unrated. Options: [0 | 1 | 2 | 3 | 4 | 5]	4

Attributes for Auxiliary Continued

Metadata Key	Description	Example
data_quality.warning Required: **False** Units: None Type: String Style: Free Form	Any warnings about the data that should be noted for users.	periodic pipeline noise
filter.applied Required: **True** Units: None Type: Boolean Style: List	Boolean if filter has been applied or not. If more than one filter, input as a comma separated list. Needs to be the same length as filter.name. If only one entry is given, it is assumed to apply to all filters listed.	True, True
filter.comments Required: **False** Units: None Type: String Style: Free Form	Any comments on filters that is important for users.	low pass is not calibrated
filter.name Required: **True** Units: None Type: String Style: List	Name of filter applied or to be applied. If more than one filter, input as a comma separated list.	counts2mv, lowpass_auxiliary
location.elevation Required: **False** Units: meters Type: Float Style: Number	Elevation of channel location in datum specified at survey level.	123.4
location.latitude Required: **False** Units: decimal degrees Type: Float Style: Number	Latitude of channel location in datum specified at survey level.	23.134
location.longitude Required: **False** Units: decimal degrees Type: Float Style: Number	Longitude of channel location in datum specified at survey level.	14.23

Attributes for Auxiliary Continued

Metadata Key	Description	Example
measurement_azimuth Required: True Units: decimal degrees Type: Float Style: Number	Azimuth of channel in the specified survey.orientation.reference_frame.	0
measurement_tilt Required: True Units: decimal degrees Type: Float Style: Number	Tilt of channel in survey.orientation.reference_frame.	0
sample_rate Required: True Units: samples per second Type: Float Style: Number	Sample rate of the channel.	8
time_period.end Required: True Units: None Type: String Style: time	End date and time of collection in UTC.	2020-02-04 T16:23:45.453670 +00:00
time_period.start Required: True Units: None Type: String Style: time	Start date and time of collection in UTC.	2020-02-01 T09:23:45.453670 +00:00
transformed_azimuth Required: False Units: decimal degrees Type: Float Style: Number	Azimuth angle of channel that has been transformed into a specified coordinate system. Note this value is only for derivative products from the archived data.	0
transformed_tilt Required: False Units: decimal degrees Type: Float Style: Number	Tilt angle of channel that has been transformed into a specified coordinate system. Note this value is only for derivative products from the archived data.	0

Attributes for Auxiliary Continued

Metadata Key	Description	Example
type Required: **True** Units: None Type: String Style: Free Form	Data type for the channel.	temperature
units Required: **True** Units: None Type: String Style: Controlled Vocabulary	Units of the data. Options: SI units or counts.	celsius

9.1 Example Auxiliary XML

```
<auxiliary>
    <comments>great</comments>
    <component>Temperature</component>
    <data_logger>
        <channel_number type="Integer">1</channel_number>
    </data_logger>
    <data_quality>
        <warning>None</warning>
        <rating>
            <author>mt</author>
            <method>ml</method>
            <value type="Integer">4</value>
        </rating>
    </data_quality>
    <filter>
        <name>
            <i>lowpass</i>
            <i>counts2mv</i>
        </name>
        <applied type="boolean">
            <i type="boolean">True</i>
        </applied>
        <comments>test</comments>
    </filter>
    <location>
        <latitude type="Float" units="degrees">12.324</latitude>
        <longitude type="Float" units="degrees">-112.03</longitude>
        <elevation type="Float" units="degrees">1234.0</elevation>
    </location>
    <measurement_azimuth type="Float" units="degrees">0.0</measurement_azimuth>
    <measurement_tilt type="Float" units="degrees">90.0</measurement_tilt>
    <sample_rate type="Float" units="samples per second">8.0</sample_rate>
    <time_period>
        <end>2020-01-01T00:00:00+00:00</end>
        <start>2020-01-04T00:00:00+00:00</start>
    </time_period>
    <type>auxiliary</type>
    <units>celsius</units>
</auxiliary>
```

A Option Definitions

Table 10: Generalized electromagnetic period bands. Some overlap, use the closest definition.

Data Type	Definition	Sample Rate [samples/s]
AMT	radio magnetotellurics	$> 10^3$
BBMT	broadband magnetotellurics	$10^3 - 10^0$
LPMT	long-period magnetotellurics	$< 10^0$

Table 11: These are the common channel components. More can be added.

Channel Type	Definition
E	electric field measurement
H	magnetic field measurement
T	temperature
Battery	battery
SOH	state-of-health

Table 12: The convention for many MT setups follows the right-hand-rule (Figure 2) with X in the northern direction, Y in the eastern direction, and Z positive down. If the setup has multiple channels in the same direction, they can be labeled with a Number. For instance, if you measure multiple electric fields Ex01, Ey01, Ex02, Ey02.

Direction	Definition
x	north direction
y	east direction
z	vertical direction
# {0–9}	variable directions