# Multi-frame Full Matrix Capture (MFMC) File Format Specification

# Version 1.0.0

## Summary

The Multi-frame Full Matrix Capture (MFMC) file format is designed for storage of data obtained from ultrasonic array probes. It has been designed specifically for the storage of the original ultrasonic data in its raw form acquired under the paradigm of Full Matrix Capture (FMC), although the format can accommodate other acquisition modalities.

The quantum of data in an MFMC file is a single frame of FMC data. A collection of frames where all acquisition parameters except the probe position are fixed constitutes a sequence. Typically, a sequence represents the results of a probe being scanned over a target. One MFMC file can accommodate multiple sequences. The number of frames in any sequence is limited only by physical storage capacity and operating system constraints, and frames can be appended to sequences within an existing file.

The underlying file format is the Hierarchical Data Format (HDF5), which is structured as a hierarchy of groups containing data-fields. A HDF5 file is a valid MFMC file, if the groups and data-fields defined by the MFMC specification are present and conform to the MFMC specification. A valid MFMC file can contain an unlimited number of additional groups and data-fields to provide additional functionality to satisfy the requirements of users.

## Introduction

\*Give the context and include at least one schematic of a typical use case (array being scanned over component with multiple frames in sequence).

## Definitions

* Element – an individually-addressable ultrasonic transduction device;
* Probe – a collection of elements, the spatial positions of which are fixed relative to one another;
* Focal law – a set of instructions that specify how a collection of elements (not necessarily in one probe) are used together;
* Transmit focal law – a focal law relating to transmission of ultrasound from a collection of elements;
* Receive focal law – a focal law relating to reception of ultrasound from a collection of elements;
* Acquisition parameters – the collection of parameters (including transmit and receive focal laws) that specify how ultrasonic data is acquired;
* A-scan – a time-domain, un-rectified ultrasonic signal (comprising amplitude measurements regularly sampled in time at a specified sampling frequency) that is recorded for a combination of transmit focal law and receive focal law;
* Frame – a collection of A-scans obtained using different transmit and receive focal laws for each A-scan;
* Sequence – a collection of frames in which all acquisition parameters except the probe position are fixed from one frame to another;
* Full Matrix Capture (FMC) – a frame of data from elements in which the transmit and receive focal laws each specify a single element and A-scans from all possible combinations of transmit and receive focal laws are recorded;
* Half Matrix Capture (HMC) – a subset of FMC where acoustic reciprocity is assumed and A-scans from only the unique transmit and receive focal law combinations are recorded;
* Probe Coordinate System (PCS) – coordinate systems (one for each probe) that describe the (fixed) relative spatial configuration of elements within each probe;
* Global Coordinate System (GCS) – the single fixed laboratory coordinate system;

## MFMC File Structure

\*explanation of template. Common points: e.g. units, character sets, byte ordering, row-major etc

### Overview and Naming Conventions

The overall structure of an MFMC file is summarised in Fig. 1.

Fig. 1 Overall file structure. User-specified groups and data-fields can be added as necessary at any level.

A HDF5 file contains a hierarchy of groups that contain datasets and attributes. The difference between datasets and attributes is that the latter are intended for small, fixed-size data, while the former are designed for holding multi-dimensional arrays of data. In all other respects their behaviour is the same and for brevity, the term datafield will be used to describe both unless stated.

Groups, datasets and attributes within the hierarchy are accessed via paths with the different levels in the hierarchy indicated by the / character. In the MFMC file, paths are capitalised, e.g.

* /GROUP\_LEVEL\_1/…/GROUP\_LEVEL\_N/DATASET\_NAME – dataset;
* /GROUP\_LEVEL\_1/…/GROUP\_LEVEL\_N/ATTRIBUTE\_NAME – attribute.

On occasions, multiple instances of the same type of group (e.g. probes) are needed at the same level in the hierarchy. These are denoted by positive, integer, numerical values appended to the group name in angle brackets, e.g. /PROBE<1>. Note that the numerical values are not numerical indices in the programmatical sense; they are just part of the sequence of characters in the path.

The notation used in this file for datafield paths is as follows

* /A\_{B/C} – shorthand for specific paths /A\_B and /A\_C;
* /A\_\* – shorthand for any paths that match pattern with \* as wildcard, e.g. /A\_B and /A\_C;
* B in /A – shorthand for path /A/B;
* /A<x> - placeholder for path indexed by numerical value x, e.g. /A<1>, /A<2> etc.

### Dimensions, Sizes and Cross-referencing

Datafields in the MFMC file are typically multi-dimensional arrays of numbers. Three types of dimension size can be identified:

* specific value – e.g. the size of the first dimension of /PROBE<p>/ELEMENT\_POSITION is always 3 as it represents coordinates in the PCS;
* variable – these are fixed at creation to specific value and may also have to be consistent with the size of dimensions in other datafields, e.g. the size of the second dimension of the three datafields /PROBE<p>/ELEMENT\_{POSITION/MINOR/MAJOR} must equal the number of elements in the probe;
* expandable – the size of these dimensions is not fixed at creation and typically represent quantities that can be appended with more data as it is acquired, e.g. /MFMC<m>/MFMC\_DATA.

Dimension sizes that are variable or expandable are identified by the variable names listed in Table 1.

|  |  |
| --- | --- |
| **Variable** | **Description** |
| N\_P | Number of probes (expandable) |
| N\_M | Number of MFMC sequences in file (expandable) |
| N\_E<p> | Number of elements in p-th probe |
| N\_F<m> | Number of FMC frames in m-th sequence of MFMC data (expandable) |
| N\_T<m> | Number of time points per A-scan in m-th sequence |
| N\_A<m> | Number of A-scans per frame in m-th sequence |
| N\_B<m> | Number of firing events m-th sequence |
| N\_L<m> | Number of focal laws associated with each frame in m-th sequence |
| N\_C<m><l>] | Number of probe/element combinations used in k-th focal law in m-th sequence |
| p | Probe number |
| m | MFMC sequence number |
| k | Focal law number |

Table 1 List of variables used in file structure description.

Some datafields contain integers that are cross-references to the indices of other entities. For example, in /MFMC<m>/COMMON the integers in TRANSMIT\_LAW\_INDEX refer to the indices of focal laws and the integers in LAW<k>/ELEMENT refer to the indices of the elements in a probe used in a focal law. Here two types of indices can be identified:

* indices to paths of groups – e.g. TRANSMIT\_LAW\_INDEX in /MFMC<m>/COMMON refers to the numbers k in LAW<k>;
* indices into dimensions of datafields – e.g. LAW<k>/ELEMENT in /MFMC<m>/COMMON indexes into the second dimension of ELEMENT\_{POSITION/MINOR/MAJOR} in /PROBE<p>.

For an MFMC file to be valid cross-referencing datafields must refer to valid indices, which means:

* paths of groups cross-referenced must exist in the file;
* indices into a datafield dimension of size N must be in the range 1...N.

### Detailed Structure

Table 2 provides the complete list of the datafields in the MFMC file specification.

| **Path** | **M or O** | **D or A** | **Class** | **Dims** | **Size** |
| --- | --- | --- | --- | --- | --- |
| /VERSION | M | A | H5T\_STRING | 1 | [1] |
| /PROBE<p>/ELEMENT\_POSITION | M | D | H5T\_FLOAT | 2 | [3, N\_E<p>] |
| /PROBE<p>/ELEMENT\_MINOR | M | D | H5T\_FLOAT | 2 | [3, N\_E<p>] |
| /PROBE<p>/ELEMENT\_MAJOR | M | D | H5T\_FLOAT | 2 | [3, N\_E<p>] |
| /PROBE<p>/ELEMENT\_SHAPE | M | D | H5T\_INTEGER | 1 | [N\_E<p>] |
| /PROBE<p>/ELEMENT\_RADIUS\_OF\_CURVATURE | O | D | H5T\_FLOAT | 1 | [N\_E<p>] |
| /PROBE<p>/ELEMENT\_AXIS\_OF\_CURVATURE | O | D | H5T\_FLOAT | 2 | [3, N\_E<p>] |
| /PROBE<p>/WEDGE\_SURFACE\_POINT | O | A | H5T\_FLOAT | 1 | [3] |
| /PROBE<p>/WEDGE\_SURFACE\_NORMAL | O | A | H5T\_FLOAT | 1 | [3] |
| /PROBE<p>/DEAD\_ELEMENT | O | D | H5T\_INTEGER | 1 | [N\_E<p>] |
| /PROBE<p>/CENTRE\_FREQUENCY | M | A | H5T\_FLOAT | 1 | [1] |
| /PROBE<p>/BANDWIDTH | O | A | H5T\_FLOAT | 1 | [1] |
| /PROBE<p>/PROBE\_MANUFACTURER | O | A | H5T\_STRING | 1 | [1] |
| /PROBE<p>/PROBE\_SERIAL\_NUMBER | O | A | H5T\_STRING | 1 | [1] |
| /PROBE<p>/PROBE\_TAG | O | A | H5T\_STRING | 1 | [1] |
| /PROBE<p>/WEDGE\_MANUFACTURER | O | A | H5T\_STRING | 1 | [1] |
| /PROBE<p>/WEDGE\_SERIAL\_NUMBER | O | A | H5T\_STRING | 1 | [1] |
| /PROBE<p>/WEDGE\_TAG | O | A | H5T\_STRING | 1 | [1] |
| /MFMC<m>/MFMC\_DATA | M | D | H5T\_FLOAT / H5T\_INTEGER | 3 | [N\_T<m>, N\_A<m>, N\_F<m>] |
| /MFMC<m>/MFMC\_DATA\_IM | O | D | H5T\_FLOAT / H5T\_INTEGER | 3 | [N\_T<m>, N\_A<m>, N\_F<m>] |
| /MFMC<m>/FIRING\_INDEX | M | D | H5T\_INTEGER | 2 | [N\_A<m>, N\_F<m>] |
| /MFMC<m>/PROBE\_POSITION | M | D | H5T\_FLOAT | 3 | [3, N\_P<m>, N\_B<m>] |
| /MFMC<m>/PROBE\_X\_DIRECTION | M | D | H5T\_FLOAT | 3 | [3, N\_P<m>, N\_B<m>] |
| /MFMC<m>/PROBE\_Y\_DIRECTION | M | D | H5T\_FLOAT | 3 | [3, N\_P<m>, N\_B<m>] |
| /MFMC<m>/COMMON/TRANSMIT\_LAW\_INDEX | M | D | H5T\_INTEGER | 1 | [N\_A<m>] |
| /MFMC<m>/COMMON/RECEIVE\_LAW\_INDEX | M | D | H5T\_INTEGER | 1 | [N\_A<m>] |
| /MFMC<m>/COMMON/PROBE\_INDEX | M | D | H5T\_INTEGER | 1 | [N\_P<m>] |
| /MFMC<m>/COMMON/TIME\_STEP | M | A | H5T\_FLOAT | 1 | [1] |
| /MFMC<m>/COMMON/START\_TIME | M | A | H5T\_FLOAT | 1 | [1] |
| /MFMC<m>/COMMON/SPECIMEN\_VELOCITY | M | A | H5T\_FLOAT | 1 | [2] |
| /MFMC<m>/COMMON/WEDGE\_VELOCITY | O | A | H5T\_FLOAT | 1 | [2] |
| /MFMC<m>/COMMON/TAG | O | A | H5T\_STRING | 1 | [1] |
| /MFMC<m>/COMMON/DAC\_CURVE | O | D | H5T\_FLOAT | 1 | [N\_T<m>] |
| /MFMC<m>/COMMON/RECEIVER\_AMPLIFIER\_GAIN | O | A | H5T\_FLOAT | 1 | [1] |
| /MFMC<m>/COMMON/FILTER\_TYPE | O | A | H5T\_INTEGER | 1 | [1] |
| /MFMC<m>/COMMON/FILTER\_PARAMETERS | O | A | H5T\_FLOAT | 2 | [2, N\_F<m>] |
| /MFMC<m>/COMMON/FILTER\_DESCRIPTION | O | A | H5T\_STRING | 1 | [1] |
| /MFMC<m>/COMMON/OPERATOR | O | A | H5T\_STRING | 1 | [1] |
| /MFMC<m>/COMMON/DATE\_AND\_TIME | O | A | H5T\_STRING | 1 | [1] |
| /MFMC<m>/COMMON/LAW<k>/PROBE | M | D | H5T\_INTEGER | 1 | [N\_C<m><k>] |
| /MFMC<m>/COMMON/LAW<k>/ELEMENT | M | D | H5T\_INTEGER | 1 | [N\_C<m><k>] |
| /MFMC<m>/COMMON/LAW<k>/DELAY | O | D | H5T\_FLOAT | 1 | [N\_C<m><k>] |
| /MFMC<m>/COMMON/LAW<k>/WEIGHTING | O | D | H5T\_FLOAT | 1 | [N\_C<m><k>] |

Table 2 List of the datafields in an MFMC file. Abbreviations: M/O = Mandatory / Optional; D/A = Dataset / Attribute; PCS = Probe Coordinate System; GCS = Global Coordinate System. Mandatory / Optional is applicable to children if parent dataset exists, i.e. a mandatory parameter in an optional group is mandatory if the group exists.

### Validity of MFMC File

An MFMC is valid if the following requirements are satisfied:

* all mandatory datafields listed in Table 2 are present;
* the class of data in datafields listed in Table 2 (whether mandatory or optional) is as specified;
* the number of dimensions of datafields listed in Table 2 (whether mandatory or optional) is as specified;
* fixed dimension sizes of datafields listed in Table 2 (whether mandatory or optional) is as specified;
* variable dimension sizes of datafields listed in Table 2 (whether mandatory or optional) are self-consistent;
* cross-referencing datafields refer to valid indices.

## Explanatory Notes

### Version – /VERSION

The MFMC version is given by a string in the form MAJOR.MINOR.PATCH (e.g. 1.0.0) according to the Semantic Versioning 2.0.0 convention [<https://semver.org/>], where {MAJOR/MINOR/PATCH} are all integer numbers without leading zeros. For development purposes the string may be appended with further information following a hyphen, e.g. 2.3.17-beta. The interpretation of the three numerical values is:

* MAJOR – for changes that require a new Application Programming Interface (API);
* MINOR – for added functionality that is backwards-compatible with existing API;
* PATCH – for bug-fixes that are backwards-compatible with existing API.

### Array Probe – /PROBE<p>

A probe group specifies an ultrasonic array that contains multiple elements. An MFMC file can contain multiple probe definitions, which are enumerated by the index <p> where p is an integer starting at 1 without leading zeros. Note that <p> is part of the string defining the name of the group in the underlying HDF5 file; it is not an index in the programmatical sense.

The defining characteristic of a probe is that the spatial location of the elements within one probe are fixed relative to each other. The positions and orientations of elements are defined in terms of a local Probe Coordinate System (PCS) for each probe. The PCS is a right-handed Cartesian system described by the axes . The recommended convention for axis orientation for array probes with elements in a single plane is as follows:

* -axis – perpendicular to plane of elements, origin in the plane of elements, positive direction orientated in direction of ultrasonic emission;
* -axis – in plane of elements, aligned to major dimension of probe, orientated in direction of increasing element index for a 1-D linear probe or in direction of most-rapidly increasing element index in the case of a 2D matrix array probe;
* -axis – in plane of elements, aligned to minor dimension of probe, orientated in direction of least-rapidly increasing element index in the case of a 2D matrix array probe.

#### Array Elements – /PROBE<p>/ELEMENT\_\*

Within /PROBE<p>, the centre of each element is defined in the PCS by ELEMENT\_POSITION. This is a [3 x N\_E<p>] array of floating point numbers, where N\_E<p> is the number of elements in the probe, the column number (i.e. 1 to N\_E<p>) is the index of the element, and the rows represent position in . The orientation of each element is defined by ELEMENT\_{MAJOR/MINOR}. These are both [3 x N\_E<p>] arrays of floating-point numbers. The columns of ELEMENT\_MAJOR and ELEMENT\_MINOR describes vectors, and , in the PCS from the centre of the respective element to one of the tips of its major and minor axes respectively. The vectors and for each element should be orthogonal and in the plane of the element. If they are not orthogonal then should be treated as correct and the component of that is orthogonal to should be used for purposes such as determining the width of a rectangular element. The vectors and should be orientated such that their cross-product, , is orientated in the direction of ultrasonic emission. The shape of an element is denoted by the integer value in the array ELEMENT\_SHAPE. Currently only rectangular and elliptical elements are supported according to:

* 1 – rectangular, dimensions by ;
* 2 – elliptical, major axis length , minor axis length .

Focused elements are specified through the optional ELEMENT\_RADIUS\_OF\_CURVATURE and ELEMENT\_AXIS\_OF\_CURVATURE datafields. These are interpreted as follows:

* Neither ELEMENT\_RADIUS\_OF\_CURVATURE or ELEMENT\_AXIS\_OF\_CURVATURE exists – elements are planar;
* ELEMENT\_RADIUS\_OF\_CURVATURE exists but ELEMENT\_AXIS\_OF\_CURVATURE does not – each element is a portion of a sphere with centre at a distance of ELEMENT\_RADIUS\_OF\_CURVATURE in the direction relative to ELEMENT\_POSITION;
* ELEMENT\_RADIUS\_OF\_CURVATURE and ELEMENT\_AXIS\_OF\_CURVATURE both exist – each element is a portion of a cylinder with axis in the direction ELEMENT\_AXIS\_OF\_CURVATURE passing through a point at a distance of ELEMENT\_RADIUS\_OF\_CURVATURE in the direction relative to ELEMENT\_POSITION.

#### Wedge – /PROBE<p>/WEDGE\_SURFACE\_{POINT/NORMAL}

These optional parameters can be used to specify the geometry of a (rigid) coupling wedge with a planar working surface. The 3 numbers in WEDGE\_SURFACE\_POINT specify the coordinates (in the PCS) of a point on the working surface of the wedge and 3 numbers in WEDGE\_SURFACE\_NORMAL specify the working surface normal vector.

\*Element position and orientation vector schematic

Fig. 1 Probe Coordinate System (PCS) and element geometry.

## Example Use Cases

\*need standard way of dumping actual file contents and displaying

# Appendix – Revision History