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The normalisation workflow and post-processing pipeline for Neutron Resonance Transmission Imaging at the INES beamline

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ABSTRACT: Neutron Resonance Transmission Imaging (NRTI) is an energy-dependent method based on event-mode acquisition of time-of-flight radiographs over a white neutron beam. NRTI enables the identification and mapping of elements and isotopes within the bulk of a sample with enhanced contrast, providing complementary capabilities of conventional imaging methods. Its growing adoption within the user community of the ISIS Neutron and Muon Source underscores the need for a standardised and reproducible data reduction framework to ensure consistent results. A dedicated effort towards its end-user optimisation is underway at the INES beamline of the ISIS facility. This work focuses on NRTI data treatment, detailing the normalisation pipeline and post-processing steps for qualitative isotopes and elements mapping. The methodology is demonstrated through a practical example, highlighting the steps required to achieve transmission data suitable for post-processing analysis.

KEYWORDS: Data processing methods; Data reduction methods; Neutron radiography

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1 Introduction

Neutron imaging is a well-established non-destructive technique providing spatial and compositional information by measuring the attenuation of a neutron beam passing through a sample. Conventional neutron imaging with cold or thermal neutrons ($E < 0.01$ eV) offers high spatial resolution — down to a few micrometers — and can be employed for quantitative evaluation of internal features dimensions and porosity. However, for composite materials or elements with similar attenuation coefficients, thermal and cold neutrons could lose discriminating power, limiting accurate elemental identification.

Energy-resolved imaging overcomes these limitations by exploiting the resonance structures characterising neutron absorption cross-sections in the epithermal energy range ($0.5\,\text{eV} < E < 10\,\text{keV}$). Resonances are unique fingerprints for each nuclide, allowing elemental and isotopic contrast that is otherwise unattainable with conventional imaging techniques [1]. Whilst resonance imaging has been successfully established at several international pulsed neutron facilities [2, 3], data reduction and normalisation often rely on bespoke or beamline-specific scripts. The workflow presented addresses the requirement for a standardised pipeline tailored to the INES beamline of the ISIS Neutron and Muon Source aimed at transitioning this methodology from a developmental stage to routine operation. The implemented pipeline (illustrated in figure 1) allows users to obtain normalised transmission data suitable for qualitative elemental and isotopic mapping, both during real-time acquisition and upon completion of the measurements.

At INES, energy-resolved neutron imaging is available for 2D and potentially 3D mapping through Neutron Resonance Transmission Imaging (NRTI) [1, 4]. NRTI is based on measuring how neutrons of different energies are transmitted through a sample. Thanks to the pulsed operation of the ISIS source (a double pulse structure with 70 ns pulse width and 320 ns peak to peak distance), neutron energies are resolved via Time-of-Flight (ToF) spectroscopy [5], which correlates the particle velocity with the arrival time at the detector. Absorption resonances appear as negative dips in NRTI transmission spectra. Their energy positions allow the identification of elements and isotopes within the specimen. This method enhances image contrast after processing, enabling the visualisation and mapping of elements that are difficult to distinguish using conventional techniques. A description of the current NRTI setup at INES can be found in [1]. The time and space-resolved detector provides a 0.8 mm pixel size, with the resulting radiographs covering a $3 \times 3\,\mathrm{cm}^2$ area, determined by the beam size. Each pixel yields a full transmission spectrum (128×128 spectra, totalling 16,384 spectra per run), enabling post-acquisition extraction of energy-resolved information from specific regions of interest.

2 NRTI normalisation workflow

Theoretical neutron transmission represents the fraction of the neutrons traversing the sample without any interaction, which is given by the Lambert-Beer law:

$$T(E) = e^{-\sum_i n_i \bar{\sigma}_{\mathrm{tot},i}(E)}$$

where $\sigma_{\mathrm{tot},i}(E)$ is the Doppler-broadened total cross-section and n_i the areal density of nuclide i [5]. Experimentally, transmission is computed from sample-in (C_{in}) and open-beam (C_{out}) spectra, after correction of background contribution ($B_{\mathrm{in}}, B_{\mathrm{out}}$) and normalisation to the total incident monitor counts $\bar{M}$:

$$T(t) = \bar{M}\frac{C_{\mathrm{in}}(t) - B_{\mathrm{in}}}{C_{\mathrm{out}}(t) - B_{\mathrm{out}}}$$

The factor $\bar{M}$ accounts for the ratio of the total intensities of the incident neutron beam during the sample-out and sample-in acquisition. Background correction [6] is necessary for quantitative analysis. In this article, only qualitative data processing is treated; therefore the correction is not applied during transmission computation.

2.1 Data acquisition

In a typical neutron imaging experiment, measurements acquired with the sample are normalised using both open beam and dark-current images, which are collected before and/or after the sample radiography. This normalisation procedure compensates for variations in neutron dose, detector response and electronic noise, ensuring that the resulting transmission data reflect only the sample's attenuation properties. NRTI produces multidimensional datasets (space, ToF, intensity) that are highly sensitive to flux variations and experimental conditions. When NRTI is performed on the INES beamline, the following sources of flux variations need to be taken into account:

- an upstream beamline is located before INES. Highly absorbing materials — such as indium sealing sample cans — may be placed in the beam during measurements that are not synchronised with those on INES. As a result, these materials can modify the energy spectrum of the neutrons incident on the sample at INES between runs;

- intrinsic flux variations can occur due to the operation of the spallation source. The combined effect of these factors may result in significant variability in the open beam spectra from one measurement sequence to another.

This has led to the adoption of an acquisition procedure based on several cycles of alternating measurements with and without the sample (open beam), each of equal duration. This approach, typically used in neutron resonance transmission analysis, ensures that the open beam reference (C_{out}) closely tracks short-term fluctuations in the neutron source or detector performance, providing a more reliable correction for time-dependent variations. For qualitative inspections, the normalised transmission can be evaluated as:

$$T(t) = \frac{1}{N} \sum_{k=1}^{N} \bar{M}_k \frac{C_{\text{in},k}(t)}{C_{\text{out},k}(t)} \tag{2.1}$$

where $\bar{M}_k$ is a factor normalising for neutron current, discussed in section 2.3, and N the total number of cycles.

2.2 Preparing the raw data

Semi-automatic Python scripts have been developed exploiting built-in tools of the Mantid environment [7] — a licence-free software widely adopted in major neutron facilities for data reduction and analysis. The first step towards visualising normalised data consists of converting the raw detector output from the proprietary `.edb` format into the NeXus format, which ensures better compliance with the FAIR data principles and is fully compatible with Mantid. Depending on the duration of a single acquisition, the raw data of each run may be distributed across one or multiple files, stored in directories named after the corresponding run number.[1] Each of these raw files is converted individually to the NeXus format using Mantid's `LoadNGem` tool. During this step, the time-of-flight (ToF) axis can be rebinned using the `Rebin` tool. By default, a uniform time binning of 1 µs is applied over the 0–1999 µs ToF range. Once re-binned, all NeXus files corresponding to a single run are merged to produce one file per run. Conversion to NeXus format typically reduces data volume by up to ~92%, significantly facilitating subsequent data handling and analysis.

2.3 Neutron current normalisation

As previously mentioned, several experimental conditions may change during an NRTI acquisition. To correct for such variations, both sample-in and open beam runs must be normalised to the incident neutron flux. The INES beamline provides an incident monitor that records this flux as a function of ToF. The implemented function `load_monitor` loads the NeXus files containing the monitor signals and directly assigns them to the sample-in and open beam runs. In principle, one sample measurement ($C_{\text{in},k}$) is normalised by the temporally closest open beam ($C_{\text{out},k}$). The function `compute_monitor_ratio` computes the monitors ratio $M_k(t)$ across the ToF of interest. If the resulting curve exhibits a constant trend — i.e. without noticeable peaks or dips — the two measurements are deemed mutually compatible for normalisation. In this case, the arithmetic mean $\bar{M}_k$ of the ratio is calculated and applied as a global scaling factor to the $C_{\text{in},k}/C_{\text{out},k}$ ratio. Conversely, any significant anomalies or non-constant behaviour in $M_k(t)$ trigger a rejection of the pair, prompting the user to select a more suitable open beam reference.

2.4 Transmission computation

The final transmission $T(t)$ is computed according to eq. (2.1). Individual NeXus datasets for each sample-in and open beam pair are imported via the `load_data` function, which crops the signals to the ToF range of interest (default: 0–1999 µs). The `compute_transmission` function then performs

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[1] The run number uniquely identifies each acquisition within the JournalViewer application, a graphical interface that parses `XML` and log data to provide metadata such as title, duration, timing, and user information.

a pixel-wise division of the workspaces and applies the monitor-based scaling factor $\bar{M}$ to account for flux variations. As NRTI characterisation often involves multiple acquisition cycles to reach a sufficient signal-to-noise ratio, the resulting normalised transmission workspaces are merged into a single dataset. To obtain a representative transmission map for the entire measurement, the workflow computes the weighted average of these cycles. This process also ensures the data remains normalised within the $[0, 1]$ range. To optimise memory performance, temporary Mantid workspaces are automatically cleared. The final dataset is exported as a NeXus file, ready for elemental mapping.

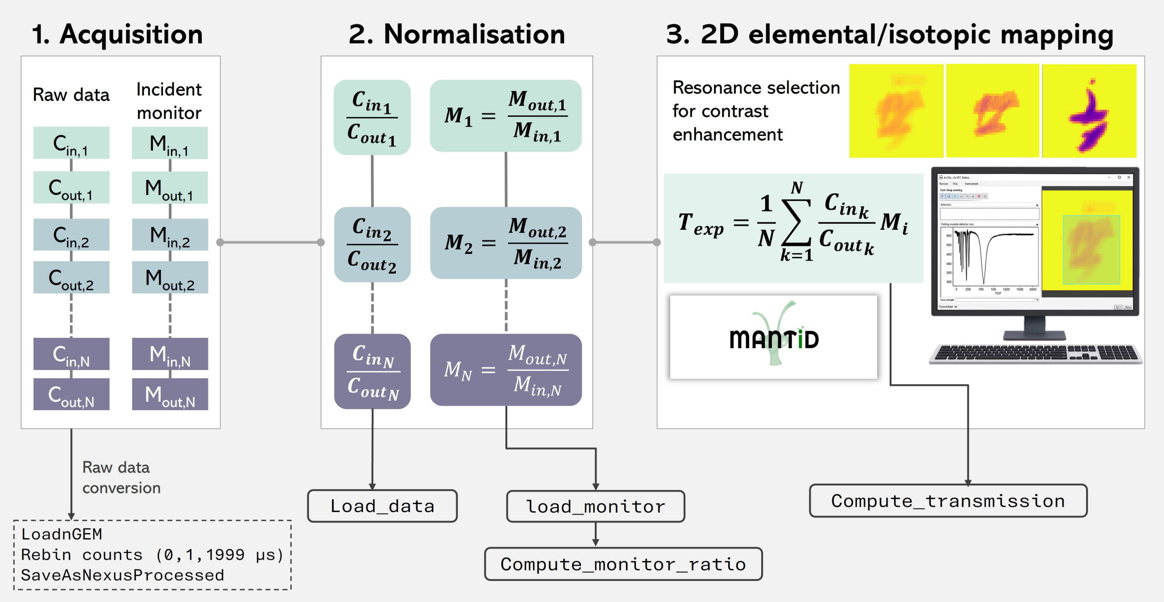

Figure 1. Schematic overview of NRTI data-reduction workflow. (1) Acquisition: alternating sample-in and open-beam runs are recorded together with incident-monitor signals. (2) Normalisation: raw data are converted to NeXus format using Mantid tools listed in the dashed box. The converted data are then imported into Mantid through the `load_data` function, which pairs sample-in and open-beam acquisitions. The same procedure is applied to the monitor data using the `load_monitor` function. The `compute_monitor_ratio` function prepares the neutron-current normalisation factor for each acquisition cycle. (3) 2D elemental/isotopic mapping: normalised transmission is computed using the developed `compute_transmission` function, which combines several runs into a single dataset. Specific resonance-energy intervals can then be selected to enhance isotopic or elemental contrast within the Mantid environment for qualitative inspection of nuclide distributions.

3 Resonance selection for elemental mapping

Normalised NRTI radiographs can be visualised within Mantid Workbench by selecting the "Show Instrument" option from the workspace context menu (right-click on the workspace). The resulting two-dimensional map depicts the transmission of the white neutron beam through the investigated specimen. Each pixel stores the corresponding relative spectrum as a function of the neutron time-of-flight.

The Instrument tab provides access to several rendering and analytical tools, including "Render", "Pick", "Draw", and "Instrument". The "Pick" and "Draw" tools enable the selection of individual pixels or the definition of regions of interest (RoI) within the two-dimensional map. Both functionalities permit the visualisation of the normalised transmission spectrum by summing the contributions over the

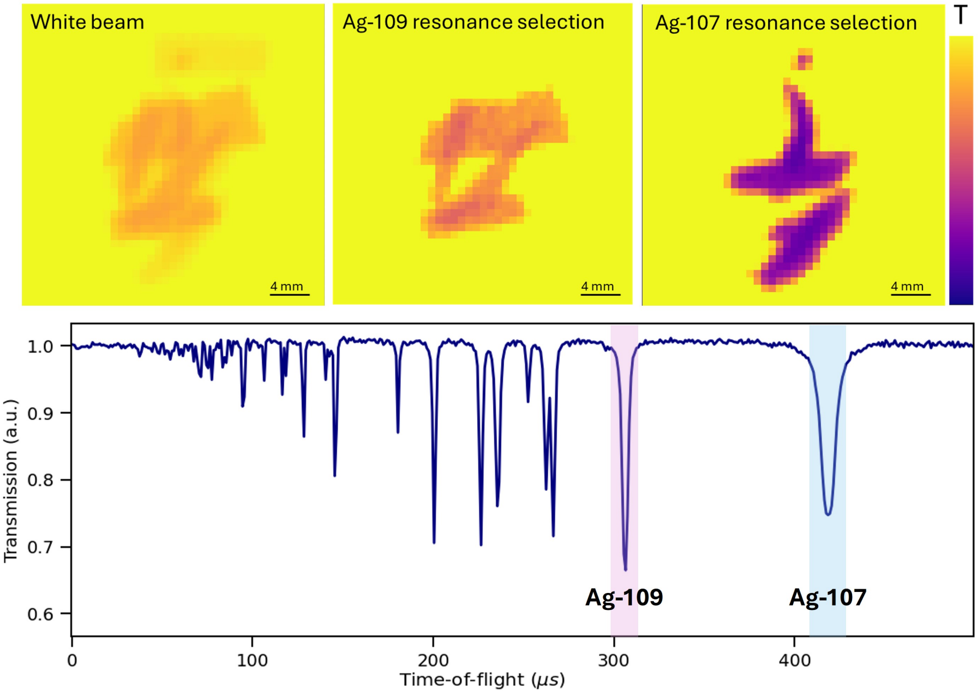

Figure 2. Resonance selection for isotopic mapping. The lower panel shows the transmission spectra of selected regions, while the upper image displays the corresponding 2D map highlighting contrast enhancement after selecting the isotope-specific resonance intervals. For the sole purpose of qualitative inspection of isotope distribution, the resonance-specific integration was performed using equivalent ToF windows of 8 µs for both isotopes, applying a shared colour scale to represent relative contrast.

selected pixels. The resulting curve, expressed as a function of ToF, can be displayed in real time (Pick) or stored as a workspace (Draw) within the Mantid environment for subsequent isotopic or elemental analysis. Once individual spectra are visualised, specific ToF regions containing non-overlapping resonances can be identified, enabling the isolation of element-specific features (figure 2).

Within the Instrument tab, the time-of-flight range control allows the user to define a narrower ToF interval encompassing resonance dips, thereby isolating the relevant transmission signal and enhancing the contrast within the radiograph. Such selective analysis facilitates a more accurate interpretation of the spatial distribution of elements and isotopes, enabling a clearer identification of compositional variations within the specimen. An example of resonance selection is presented in figure 2. The sample consists of silver flakes with controlled isotopic enrichment, of type 99.7% ^{109}Ag and 99.5% ^{107}Ag, which are randomly arranged and partially overlap. Using the “Draw” tool, a RoI encompassing the entire sample was selected. The corresponding transmission spectrum is shown in the lower panel, with the selected resonances used to enhance contrast. The upper panel displays, respectively, the epithermal radiography and the images with contrast enhancement following resonance selection.

4 Conclusions

An end-user normalisation workflow and post-processing pipeline tailored for Neutron Resonance Transmission Imaging has been presented. The proposed procedure addresses the main challenges specifically encountered with energy-resolved neutron imaging at the INES beamline of the ISIS

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Neutron and Muon Source. The acquisition and normalisation of NRTI data is a complex and time-consuming procedure. This paper presents research conducted in partial fulfilment of the author's PhD degree. The study aims to establish a reproducible and easy-to-use methodology to support the growing NRTI community and improve technical preparation for routine application. By integrating neutron-current monitoring, pixel-wise normalisation, and resonance-based contrast selection within the Mantid framework, the workflow provides users — including those with limited programming experience — with a reliable tool for obtaining normalised transmission datasets during or immediately after acquisition, improving experimental feedback, and facilitating informed decisions during beamtime. Examples of isotopic mapping illustrate how resonance selection analysis enhances contrast and allows precise visualisation of the spatial distribution of targeted nuclides. This workflow represents a foundational step toward the full integration of NRTI as a routine technique at large-scale facilities. Future developments will focus on quantitative analysis, background correction standardisation, and automated resonance identification, ultimately extending the NRTI capabilities to routine 3D isotopic imaging and advanced material characterisation.

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