Helical sample-stepping for faster speckle-based multi-modal tomography with the Unified Modulated Pattern Analysis (UMPA) model

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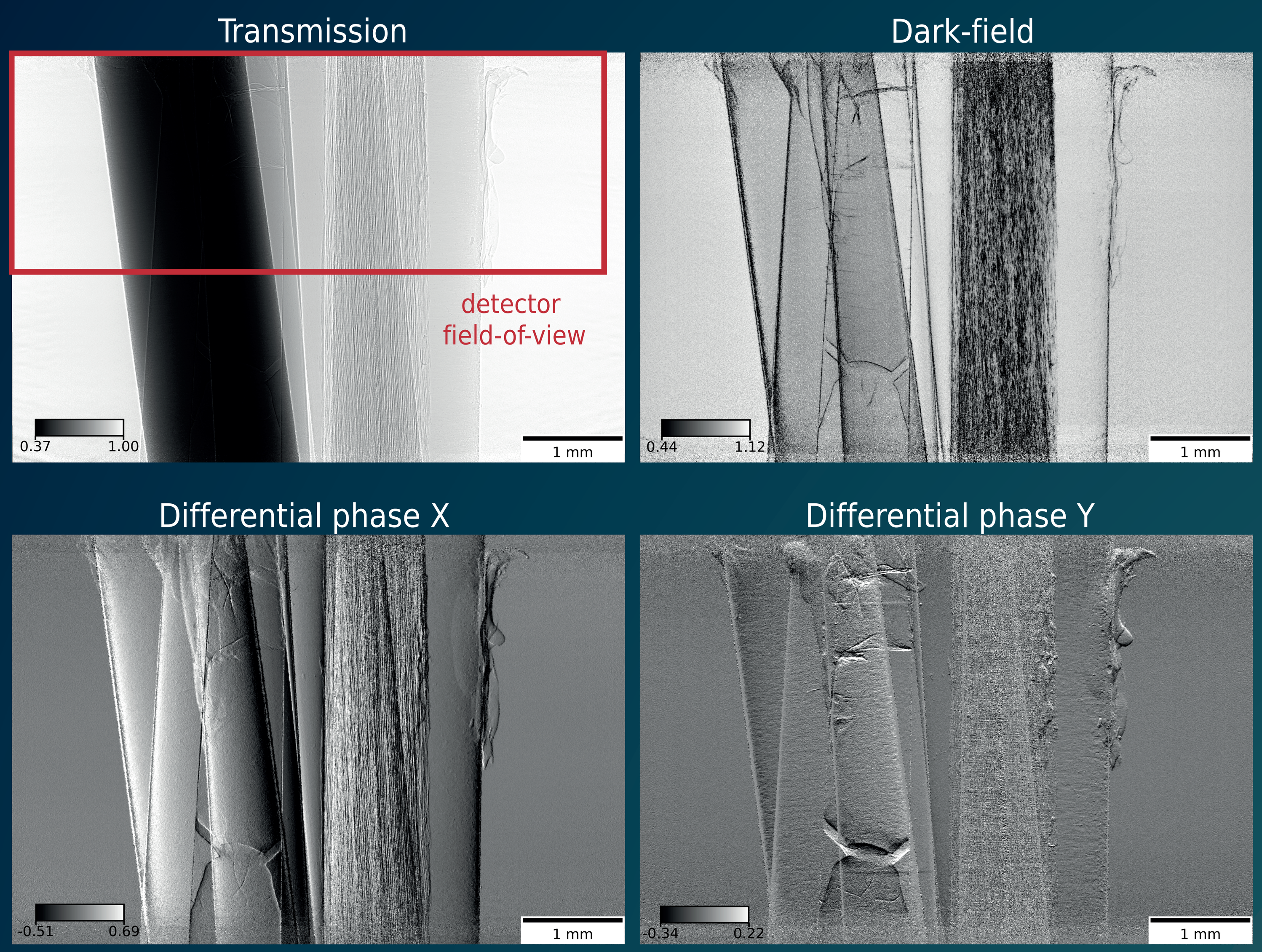
Multi-modal tomography with near-field speckles

Speckle-based imaging (SBI) is a multi-modal X-ray imaging technique that gives access to *absorption, phase-contrast*, and *dark-field signals* from a single dataset.
However it is often difficult to disentangle the different signals from a single measurement.
In order to retrieve the different channels, SBI relies on a reference speckle pattern, generated by the addition of a wavefront marker in the beam [1,2] (i.e., a sandpaper). **Here, we show how a continuous helical acquisition can extend the field-of-view (FOV) and speed up the acquisition while maintaining a multiframe approach for the signal retrieval of a test object.**



UMPA reconstruction: imaged phantom, example of the retrieved information for a single angle after analysing the dataset with UMPA. The differential phase signals can be integrated to retrieve the phase information.

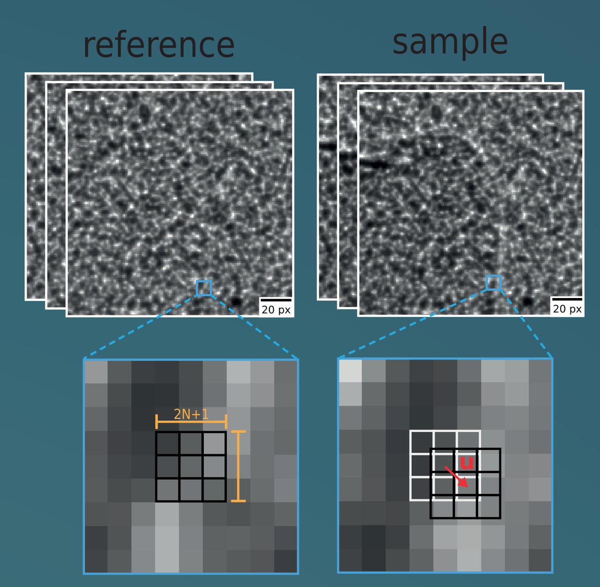
The Unified Modulated Pattern Analysis (UMPA) model for continous acquisition schemes

By solving a least squares problem (1-3), the speckle pattern enables UMPA [3,4] to retrieve multiple image channels (transmittance T, differential phase shifts $\boldsymbol{u}$ and dark-field D).
The method can be used for *single-frame* acquisitions, requiring just one reference and one sample frame. However, the estimation of the image signals is sample- and speckle-dependent. By scanning multiple reference and sample images with different relative transverse movements between modulator and sample, it is possible to obtain more accurate reconstructions and improve image quality.

$$I^{(model)} = T\{D[I_0(\boldsymbol{r}-\boldsymbol{u}) - \langle I_0\rangle(\boldsymbol{r}-\boldsymbol{u})] + \langle I_0\rangle(\boldsymbol{r}-\boldsymbol{u})\} \qquad (1)$$

$$\langle I_0\rangle(\boldsymbol{r}) = \frac{\sum_{w_x=-N}^{N}\sum_{w_y=-N}^{N}\Gamma(\boldsymbol{w}) I_0(\boldsymbol{r}+\boldsymbol{w})}{\sum_{w_x=-N}^{N}\sum_{w_y=-N}^{N}\Gamma(\boldsymbol{w})} \qquad (2)$$

$$\mathcal{L}(\boldsymbol{r};\boldsymbol{u},T,D) = \sum_{m=1}^{M}\sum_{w_x=-N}^{N}\sum_{w_y=-N}^{N}\Gamma(\boldsymbol{w})\left[I_m^{(model)}(\boldsymbol{r}+\boldsymbol{w};\boldsymbol{u},T,D) - I_m(\boldsymbol{r}+\boldsymbol{w})\right]^2 \qquad (3)$$

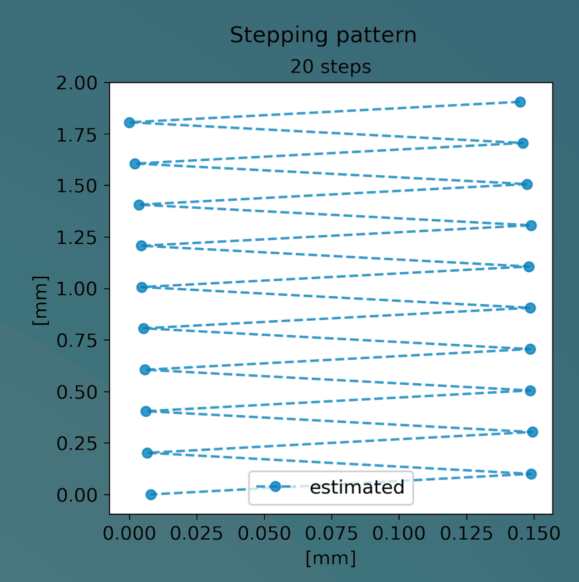


UMPA model: example of collected raw data, reference and sample frames. UMPA fits a model per pixel that accounts for speckle change in intensity, shift and blurring in an analysis window of tunable size.

Diffuser stepping:
Standard approach.
- The *modulator moves* between every tomographic acquisition.

Sample stepping:
Recently implemented.
- The modulator remains in place while the *sample moves* on a grid pattern.

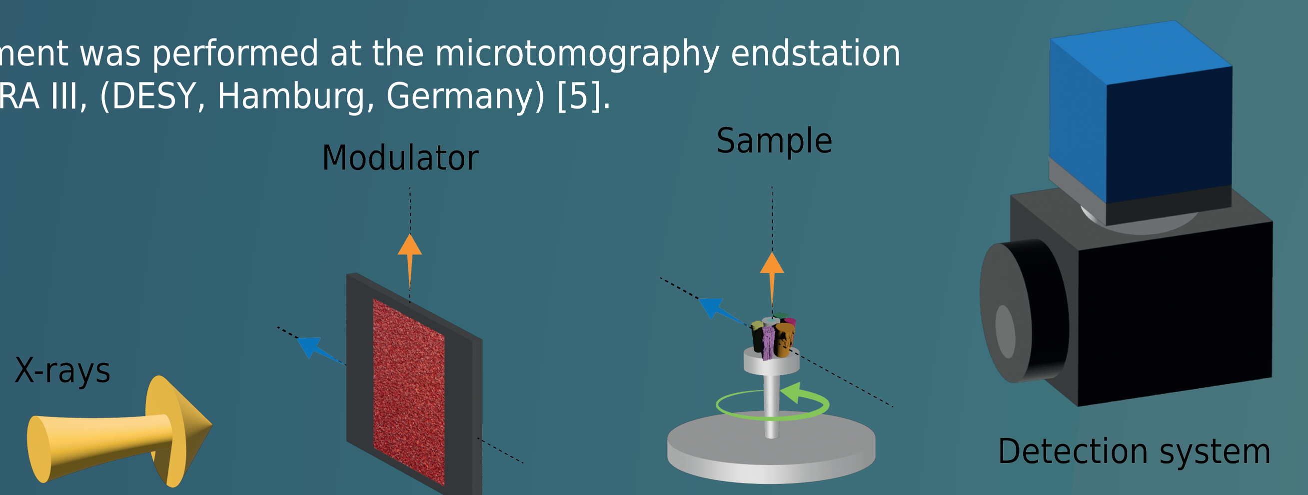
Helical stepping:
New acquisition and reconstruction approach.
- The *modulator remains in place* while the *sample continously rotates and translates vertically.*
- Every 180° the sample is seen from the same angle but at a different relative modulator position (due to the vertical translation).
- The sample positions are estimated with cross-correlation methods using the transmission channel from UMPA.
- Any modulator drift results in an offset in the differential phase signals obtained by processing every position as single-frame UMPA.



Sample positions: translation of the sample during the helical scan, as determined from the data. The sample positions are required for the algorithm, as it has to knows where to move the analysis window between the different steps in the set of sample and reference images ($\mathbf{r}$ centers the analysis window on the same sample feature $\forall m$ in (1-3)).

Experimental setup

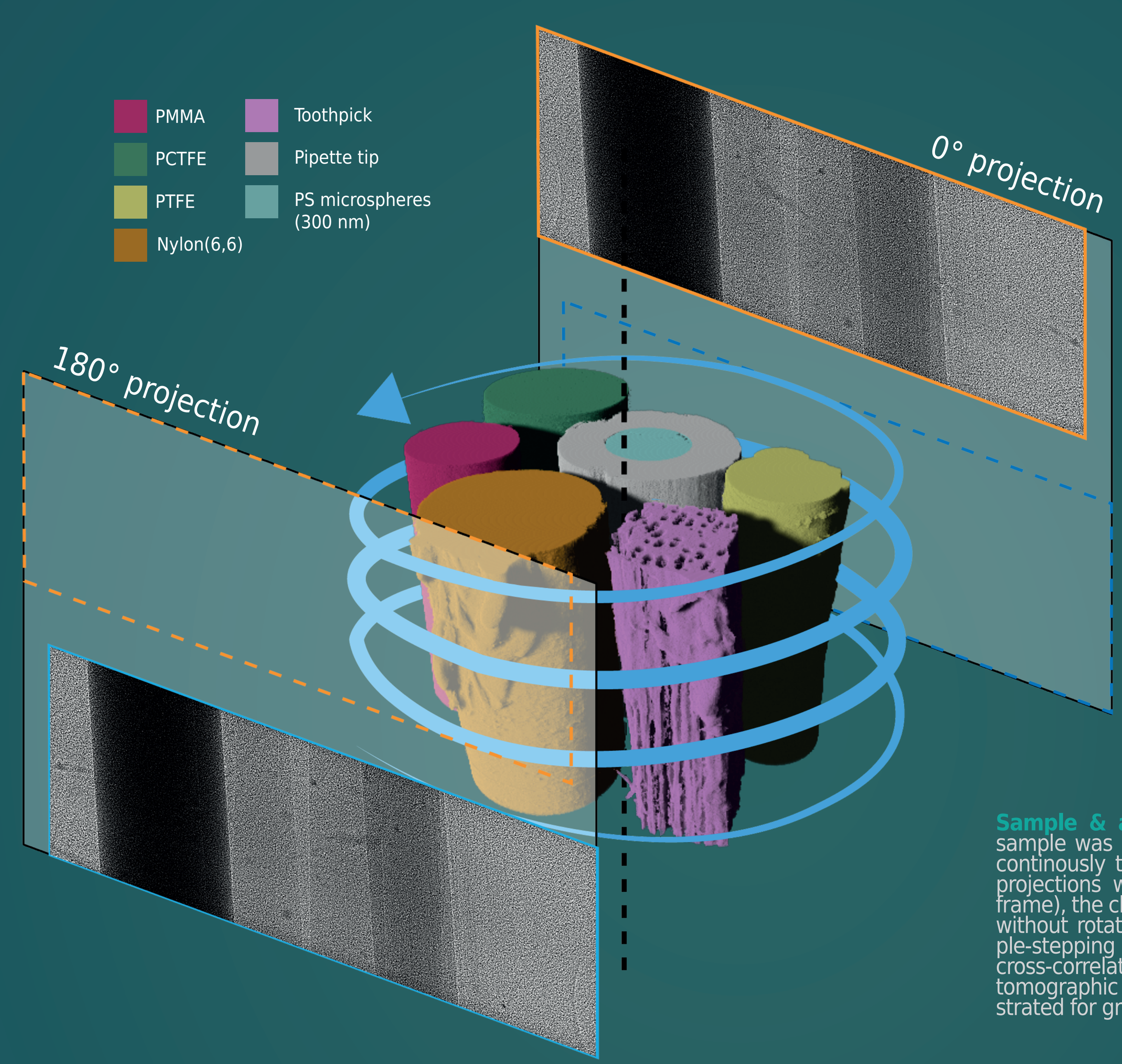
The experiment was performed at the microtomography endstation at P05, PETRA III, (DESY, Hamburg, Germany) [5].



Source:
- Monochromatic beam of 20 keV from an undulator insertion device.

Detection system:
- CMOSIS CMV 20000 camera from Karlsruhe Institute of Technology (6.4 µm pixel size)
- Optical microscope (×5 magnification) + 100 µm CdWO4 scintillator
- FOV (1951 px × 5120 px), 2.50 mm × 6.55 mm (1.28 µm pixel size at the sample plane)

Sample:
- Phantom composed of multiple plastic rods (PMMA, PTFE, PCTFE, Nylon-6,6), a piece of wood, and 300 nm-diameter PS microspheres (see Figure on the right).
- Placed 175 mm from the detector, roughly 58 m from the source.
- Modulator (6 layers sandpaper P1000 grit) mounted 115 mm upstream of the sample.



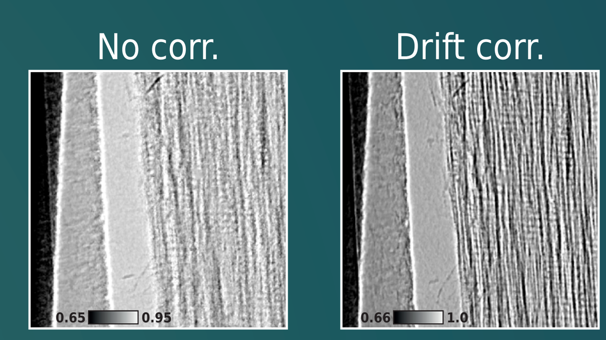
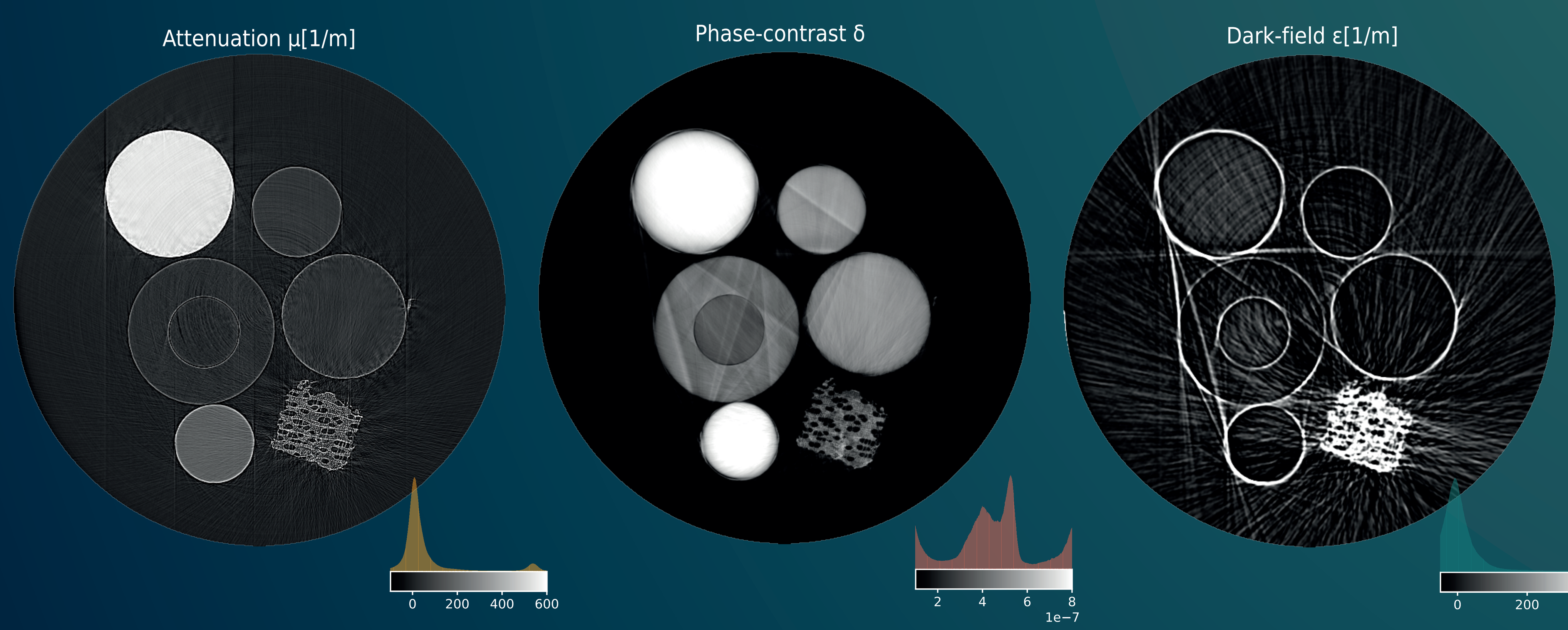


Image corrections: UMPA reconstruction with 20 steps, transmission image detail (500 px × 500 px) before and after applying modulator and sample drift corrections. Sample features are more visible.

Sample & acquisition scheme: for the helical-stepping acquisition the sample was rotated 10 times by 360° around the center of rotation while continously translating vertically. In such a way, considering the subset of projections with an interval of 180° between them (flipping every other frame), the change between frames is a net vertical movement of the sample without rotation. Such dataset can be processed with UMPA with the sample-stepping modality. The sample position per step can be estimated using cross-correlation methods. In a helical scan, this can be repeated for every tomographic angle between 0° and 180°. A similar method has been demonstrated for grating-based imaging [6].



Multi-channel volumes: same slice through the different volumes after tomographic reconstruction. Histograms of the image values are shown on top of the colorbar. Attenuation shows edge-enhancement from fringes generated at air-material interfaces due to the good source coherence. They affect the correct intepretation of the sample's edges in UMPA as their formation is not included in the model, showing an increased number of artifacts in the integrated phase and dark field volumes too.

Challenges

1. Data size & computation
- 10 milion pixels per frame, thousands of projections and 20 steps generate terabytes of data, processing is demanding and the reconstructions can be difficult to handle.

2. Drift correction & sample position refinement
- We use UMPA itself to assess sample and modulator drifts between the different steps, this is an essential point in processing data from continuous scans at high-resolution.

Conclusion

The standard diffuser stepping and the novel helical stepping reconstructions delivered comparable results. However, while the standard approach yielded a vertical FOV of 2.5 mm in about 115 minutes, helical stepping gave 4.4 mm in 49 minutes.

With this work, we highlight the potential of SBI and UMPA to obtain multimodal volumetric data of objects larger than the detector's FOV. Using continuous acquisition schemes can reduce scan times, while any redundant information is still maintained and incorporated in the reconstruction with UMPA.

References

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