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# Master-Slave principle applied to an electrically-tunable swept source-OCT system

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## ABSTRACT

In this communication, we evaluate the suitability of Master-Slave (MS) optical coherence tomography (OCT) for processing of interferograms generated by an interferometer driven by an akinetic, electrically-tunable swept source from Insight with an ultra-large instantaneous coherence length. The akinetic source is programmed to sweep linearly, but within the sweep, at predictable times, the laser tuning introduces invalid regions in the interferogram, which are normally removed post-acquisition using a pre-calibration file. This makes sure that any optical frequency component is used once only and enables correct operation of a Fourier transform (FT). A FT applied to an unprocessed emitted spectrum leads to wide and numerous peaks in the A-scan. MS processing was introduced to avoid the necessary corrections demanded by conventional FT signal processing or its derivatives.

The MS procedure consists of comparing photo-detected signals at the output of two interferometers, a Slave and a Master interferometer. The MS method was advanced along two avenues, either by using (i) electrically-generated master signals (making use of the same interferometer twice) or (ii) optically-generated master signal via a recently introduced MS down-conversion procedure. We apply both avenues to the Insight source. Approach (i) tests the MS principle as an alternative to the Insight file correction while (ii) demonstrates near coherence-limited operation at a large axial range ($> 80$ mm) for which a too-high sampling rate digitizer would have been needed.

In this communication, we evaluate for the first time the suitability of the MS procedure to OCT measurements performed with the akinetic swept source commercialized by Insight. Two modalities are evaluated to implement the MS processing, based on: (i) digital generation of the master signals using the OCT interferometer and (ii) down conversion using a second interferometer driven by the swept source.

**Keywords:** swept source optical coherence tomography, Master-Slave optical coherence tomography, akinetic swept source, novel swept source configurations, spectral processing

One of the main strengths in swept-source OCT is the large axial imaging range, enabled by long instantaneous coherence lengths. Recently reported swept source technologies[1,2] present coherence lengths in the order of meters. However, swept source OCT still lags behind spectral-domain OCT systems when it comes to phase stability, namely due to A-scan trigger jitter associated with the different tuning modalities. Electrically-tunable optical sources, such as the ones developed by Insight, are akinetic by nature, therefore less prone to phase instabilities,[3] while presenting long instantaneous coherence lengths (over 200 mm). Moreover, the tuning rate and tuning range can be easily reconfigured by changing the electronic driving signal, allowing extra flexibility and high A-line rates (over 600 kHz) in their use.

The tuning procedure employed by the Insight source is based upon Vernier tuning of multiple sections within an all-semiconductor laser structure. Using this tuning mechanism, the laser may be swept over a wide wavelength range, in a single longitudinal laser mode, with a linear sweep of optical frequency versus time within valid regions of the sweep. Sporadically during the sweep, the tuning mechanism also introduces brief portions of time during which the laser's optical frequency is not swept linearly. These regions of the interferogram time-record repeat deterministically and therefore can be determined by the calibration routine prepared for each source, and once such regions are known, they can be eliminated. The laser generates a data-valid vector (DVV), which specifies the samples of the time-record that are valid while the invalid data (which may account for 25% of the total samples in a 100 kHz A-scan) are removed from the output interferogram prior to processing. An advantage of the akinetic source is that the valid data are already $k$-space linearized, meaning that once the

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invalid data are removed, no further k-space resampling or optical $k$-clock is needed prior to FFT application. However, the removal procedure requires a strict synchronous clock and delay compensation between source and digitizing hardware.

MS-OCT,[4] and its complex-valued variant,[5] carry out the processing of the raw OCT data in a different form - instead of employing a FT, MS-OCT performs a comparison of the raw OCT data against either: (i) pre-recorded (or pre-generated) spectra for all axial positions considered, or (ii) against a "live" comparison spectrum provided by a second optical interferometer (the down-conversion Master-Slave procedure). Due to this particularity (comparing like with like), MS-OCT tolerates chirped data and therefore no extra processing is needed on the data. Effectively, MS-OCT implements a "calibration" of the system that makes the whole operation tolerant to both the chirp due to nonlinear sweeping as well as to dispersion left not compensated in the interferometer,[6] enabling swept-source operation without a $k$-clock.[7]

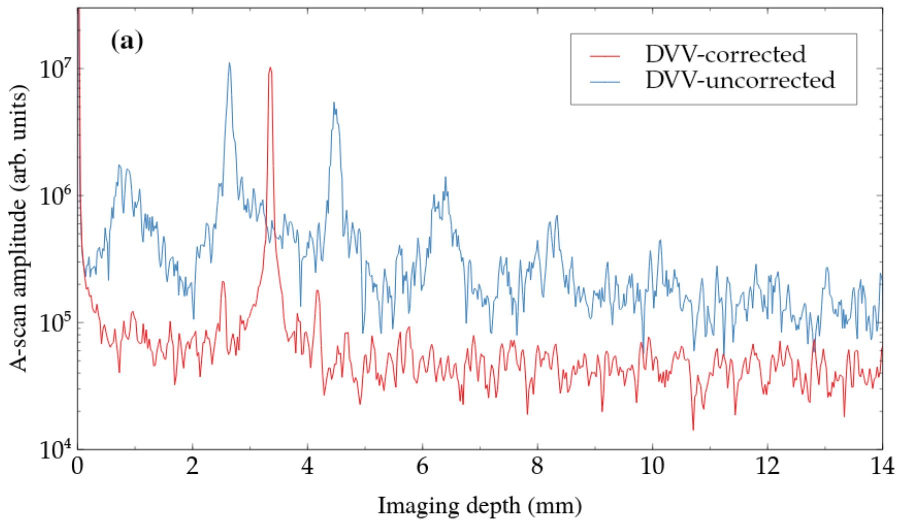
In this communication, we assess the suitability of MS-OCT processing applied to the Insight source. Due to the nature of MS-OCT, we conjecture that we should be able to use the source without the DVV-based correction, and, ultimately, without the need for an external clock (from the optical source), thus somewhat simplifying the overall system. Unlike our earlier studies with the MS-OCT method, in this case the comparison against the "master" interferometer involves more than one frequency in the interferogram, as either spectra being compared present such spectral intervals where similar frequencies in the output spectrum distort the interferogram.

The Insight source (model SLE-101) was used throughout the study with a sweep rate of 100 kHz and the maximum tuning range setting (roughly 90 nm). At the sample clock frequency setting used (400 MHz), a maximum of 4000 sampling points are enabled, reduced by approximately 25% when the DVV was used. The source was paired with a fiber-based Michelson interferometer (Slave), with recirculating reference path and terminated on a balanced single mode splitter to drive an Insight balanced photodetector unit (with a cut-off frequency of 400 MHz) and digitised using an AlazarTech ATS9350 board (max sampling rate 500 MS/s).

For the first part of the study, a single interferometer configuration (with a single reflector in the object arm, generating a single modulation frequency in the interferogram) was used. We first performed a frequency characterization of the interferogram for the case where the DVV correction is applied (which is the typical usage scenario for these sources) versus the case where the DVV correction is not applied. In the latter case, the invalid signal regions are present within the interferometric signal, introducing additional frequencies as depicted in the blue trace in Fig. 1(a). These additional frequencies, when not eliminated, not only degrade the A-scan, but they also move the main A-scan peak in the depth direction (the two graph sets in Fig. **??** (a) were acquired at exactly the same OPD).

Afterwards, we used the MS-OCT method for 3 sampling/processing protocols to obtain the A-scan for a single reflector as shown in Fig. 1(b). To obtain all these traces, a channeled spectrum was firstly acquired at the depth where the single reflector was located. This spectrum was then Hilbert-transformed to produce a "complex mask" that was employed in our software for Complex Master Slave processing To obtain the A-scan, the translation stage TS in the interferometer was configured to move over a range of 4 mm, whilst constantly acquiring "slave" spectra, which were compared against the complex mask.

Using the clock provided by the optical source and DVV correction (blue trace in Fig. 1), as expected a single, neat and clean A-scan is obtained with a good signal to noise ratio. Using the clock provided by the optical source but no DVV correction (red trace in 1) a single peak is re-obtained, with some more noise. Again, a single peak is obtained even when not employing the optical source clock (asynchronous operation, hence no DVV correction possible), as depicted by the green trace, and with similar noise as the red curve. While an increase in the noise floor is observed for the two cases where DVV correction was not applied, no additional peaks are present in the A-scan, and the peak width is conserved throughout the three processing protocols. Moreover, due to the tolerance to dispersion imbalance in the interferometer, which is inherent to the MS-OCT method,[6] a slight reduction in the peak width was obtained, from over 12-16 microns using the Fourier-transformed results of Fig. 1(a) ($\sim 12-16\,\mu$m, depending on the OPD setting) when the DVV correction and FFT are applied, to roughly 12 microns when MS-OCT is used over the data with the DVV correction. The coherence-limited resolution of this system was calculated (using the procedure described by Rivet *et al.*[5]) to be 11.6 $\mu$m.



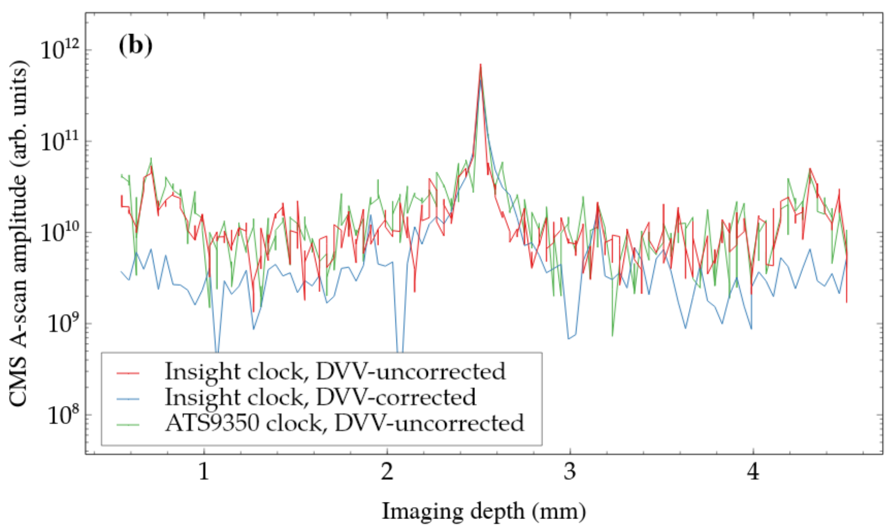




Figure 1. Experimental results obtained with the Insight source. **(a)** conventional (FFT based method), A-scans for a single reflector at an imaging depth of 2.5 mm, when the interferogram was corrected with the DVV (red) and when that correction was not applied (blue). **(b)** Master-Slave using electrically generated master signals (masks), A-scan for a single reflector at roughly the same imaging depth, obtained with the source's built-in clock and DVV correction (blue), the source's built-in clock but no DVV correction (red), and the AlazarTech digitizer's built-in clock (green).

In a second experiment, the down-conversion Master-Slave method reported by Podoleanu *et al.*[7] was tested, on a long axial range (> 80 mm) swept-source-based system. To this goal, an additional optical interferometer (Master) was set up with a similar optical path difference as the interferometer presented above (Slave); these two interferometers were both fed by the Insight source using a 60/40 fused fiber-based directional coupler.

A Thorlabs InGaAs amplified AC-coupled photo-detector with a cut-off frequency of 350 MHz was used in the second interferometer (Optical Master). This procedure was tested at a very large range of 8 cm, where the frequency of the photo-detected signal exceeds 400 MHz. The Nyquist limit of the digitizer board used earlier in the study is 250 MHz, therefore the board would have not been able to sample the resulting interferogram. To evaluate the axial resolution in this case, similar to time domain OCT, the OPD in one of the two interferometers is scanned mechanically. This leads to the graph in Fig. 2. This is not, however, the way the down-conversion method is used, where no mechanical scanning is applied, simply the Master interferometer provides the gating signal for selecting channeled spectra of similar modulation from a depth in the tissue (object) where the OPD

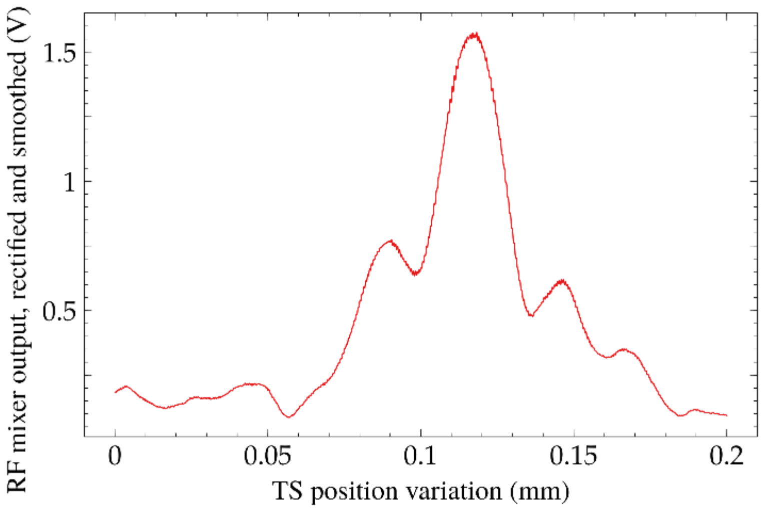



Figure 2. A-scan obtained with the down-conversion procedure, with the master interferometer having an OPD of $\sim 80\,\text{mm}$, and the reference arm of the slave interferometer being mechanically scanned over a range of $200\,\mu\text{m}$ at $\sim 80\,\text{mm}$ OPD. The main peak has a FWHM of $\sim 28\,\mu\text{m}$, which corresponds to an axial resolution of $\sim 14\,\mu\text{m}$ due to the double-pass interferometer configuration.

in the slave interferometer matches the OPD in the Optical Master.

The second interrogating interferometer acts as an Optical Master. In this way, processing the down-converted signal up to twice the sweeping frequency, a down-conversion factor of $N = 500\,\text{MHz}/200\,\text{kHz} = 2500$ is obtained. This means that the bandwidth of the signal from the photo-detector was reduced by a factor of 2,500. The A-scan peak obtained using the down-conversion method exhibits a width of $14.2\,\mu\text{m}$, slightly larger than the expected $11.6\,\mu\text{m}$. This is explained by some dispersion difference between the two optical interferometers which reduces the bandwidth within which the channeled spectrum modulation is sufficiently similar at the two interferometer outputs, and this can additionally explain the presence of the side-lobes and limited peak-to-noise ratio. However, this may be a price worth paying given the low cost route allowed by down-conversion. Due to the comparison operation being carried out prior to digital acquisition, it is possible to employ lower-cost, lower sampling rate hardware to sample the resulting signal by the factor $N$ of down conversion.

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