# Data Acquisition in Laser Spectroscopy for Probing Ultralight Scalar Dark Matter Field Induced Oscillations

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***Abstract*—Data acquisition is addressed in a dark matter direct detection experiment that monitors oscillations of the absorption signal in laser spectroscopy. The approach is based on a laser locked to an ultrastable cavity and disseminated remotely by optical fiber links that probe acetylene reference transitions in the spectral domain at 1.5 µm. This contribution proposes the design of a triggerless, continuous, and independent data acquisition system with sampling rate at hundreds MSPS level and accurate timestamping provided by global reference clocks.**

***Keywords—dark matter detectors, data acquisition concepts, timestamping, laser spectroscopy, optical fiber links.***

## I. INTRODUCTION

It is widely recognized that the matter in our Universe is primarily made of dark matter (DM). Its mass, spin, and interactions with Standard Model (SM) fields is still unknown. Many theoretical models assume that DM is made of spin-0 particles with sub-eV mass that behave locally as classical fields oscillating at the corresponding Compton frequency. Interaction of this ultralight scalar dark matter (USDM) field with the Standard Model fields may induce violation of Einstein equivalence principle and oscillations of the fundamental constants [1]. That translates into oscillations of the energies of molecular and atomic levels and of the lengths of solids. Here, USDM couplings to SM matter are addressed by laser spectroscopy of molecules by monitoring the oscillations of the absorption signal. In previous approaches [2-4], the absorption signal was recorded in function of time (periodograms) and Fast Fourier transform of the averaged data was performed up to 250 MHz. The actual needs are for robust, fast, and reliable data acquisition systems with increased acquisition time and more data to reduce noise by averaging, data recording with high duty cycle to enable detection of fast transients, high speed in data acquisition and data processing to manage increased Compton frequencies, and, finally, effective timestamping of data to enable correlation of periodograms.

## II. USDM DETECTION APPROACH

The proposed dark matter direct detection system is based on a fiber network of laser spectroscopy experiments. A laser at 1542 nm, locked to an ultrastable cavity and disseminated remotely by optical fiber links [5], is tuned at a frequency $f_L$ nearly to the frequency of an acetylene reference transition $f_{mol}$. Here we are interested by the spectrum of the frequency deviation $\Delta f(t)/f = \left(f_{mol}(t) - f_L(t)\right)/f_L(t)$ where $f = f_L \approx f_{mol}$. Each frequency has a specific dependence on each fundamental constat $g$ (among the fine structure constant $\alpha$, proton-to-electron mass ratio $\mu$, and ratio between mean quark masses $\hat{m} = (m_u + m_d)/\Lambda$ to the QCD mass scale $\Lambda$, for example). The dependence is quantified with the appropriate sensitivity coefficients $Q_{mol,L}^{(g)} = \partial ln f_{mol,L}/\partial ln g$ that are provided by atomic, molecular or nuclear physics theories.

In some USDM models, an oscillating field $\varphi(t) \approx \varphi_0 \cdot \cos\left(2\pi f_\varphi t\right)$ of amplitude $\varphi_0$ and Compton frequency $f_\varphi$ couples to the SM fields and yields oscillations of the fundamental constants $g(\varphi) = g\left(1 + d_g \varphi\right)$ that are driven with the relevant coupling constants $d_g$. Fluctuations of the fundamental constants are related to frequency fluctuations $\frac{\Delta f(t)}{f} = \sum_n \left(Q_{mol}^{(g_n)} h_{mol}\left(f_\varphi\right) - Q_L^{(g_n)} h_L\left(f_\varphi\right)\right)\frac{\Delta g_n}{g_n}$. Response of the experimental setup to the fluctuations of the fundamental constants is taken into account with $h_{mol,L}\left(f_\varphi\right)$ dependences that have to be determined experimentally.

In the laser spectroscopy experiment [6], as shown in Fig. 1, the laser frequency is slightly detuned to the molecular frequency. Time dependence of the molecular absorption signal $V(t) = D\Delta f(t)$ may be related to the fluctuations of the frequency detuning and the experimental sensitivity coefficient $D$.

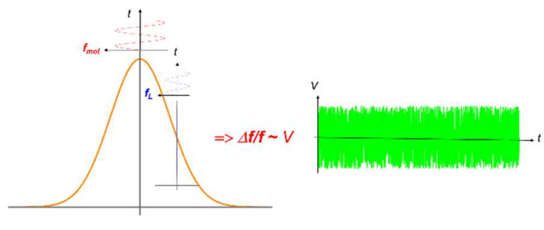


Fig. 1. Principle of the experiment.

## III. EXPERIMENTAL SETUP

Direct detection of USDM by laser spectroscopy requires optical to electrical signal conversion, data acquisition system and software to measure oscillations of the optical signal at the Compton frequency of the USDM field. The parts of the data acquisition system are indicated in Fig. 2.

Frequency bandwidth of this approach is limited by the experimental response functions. A cutoff of $h_{mol}\left(f_\varphi\right)$ is imposed by the linewidth of the molecular line. Typical values are at the 100 kHz level in saturated absorption spectroscopy and up to the 1 GHz level in Doppler-limited spectroscopy.

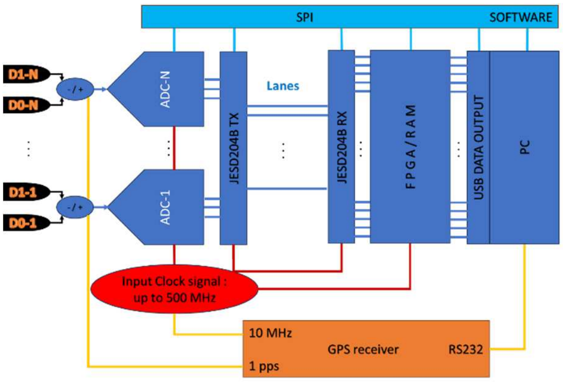


Fig. 2. Implementation of the data acquisition system.

Low-noise optical to electrical conversion in the experimental setup is provided with a differential detector (Thorlabs PDB781CAC) with frequency bandwidth of 1 MHz – 2.5 GHz, conversion gain at the $10^3$ V/W level, common mode rejection ratio >20 dB, and overall output voltage noise $\delta V < 3$ mV RMS.

The first requirement from the data acquisition system is to record and store data. That must be done by minimizing dead time and, ultimately, by continuous operation. Data from each detector channel has to be recorded with high speed, high resolution and accurately timestamped using a reference clock signal. Low time jitter $t_J$ of the clock signal is required because it impacts the theoretical signal to noise ratio performance in function of the frequency $f_{IN}$ of the sampling system $SNR = 20 \log_{10}\left(\frac{1}{2\pi f_{IN} t_J}\right)$. The response of the system in the detection bandwidth range has to be calibrated against reference oscillating signals. Finally, an amount of data recorded during a sampling time interval $T_c$ has to be transferred and stored to a computer. The software has to provide averaging of samples over an integration time $\tau$ and to provide Fast Fourier transform (FFT) of the averaged data. Timescales for $T_c$ and $\tau$ should be adjustable, as well as the FFT frequency bin window.

Data acquisition is performed here with an Intersil's high speed analog to digital conversion evaluation board. The hardware consists in an ISLA214S50IR48EV1Z daughter card and a ADCMB-HSFMCEV1Z motherboard.

The daughter card uses an ISLA214S50 14-Bit analog-to-digital converter (ADC). A sinusoidal clock input with frequency up to 500 MHz drives the sampling rate by harmonic clocking. The device uses two time-interleaved 250 MSPS ADC units leading to ultimate sampling rate of 500 MSPS. Analog inputs are driven differentially with an ideal full-scale input voltage of 2 V centered on the 1 V common mode output voltage. The best SNR at 500 MSPS is 73 dBFS.

The motherboard uses an interface implementing the JESD204B industrial protocol [7]. It enables synchronized multigigabit serial data link between the two ADCs and the data receiver that is a field-programmable gate array (FPGA). Communication is established over two or three programmable serial lanes. The clock signal for the JESD204 link is generated in the daughter card and is routed to the ADCs and to the FPGA. Each lane data rate may be up to 4.375 Gbps. The FPGA routes data output to the memory banks before passing to a PC via the USB interface at lower speed for processing with software. The hardware allows recording of a maximum of $2^{25}$ data points that is software-limited at $2^{20}$ data points.

The software (iEvalADC, proprietary Intersil) is installed on a PC under Windows XP operating system. It allows programming data acquisition via its Serial Peripheral Interface (SPI) port, reading data from the FPGA, saving to the PC memory and post-processing (data input/output on PC hard-disk, data visualization and FFT analysis). The software defines the number of data points captured per acquisition cycle. The software allows single-shot or continuous data capture and dumping the raw data points to the PC. The sampling rate and the JESD204B clocking frequencies are software defined and calculated in hardware from the value of the clock frequency provided on the daughter card. The FFT analysis of the samples is provided with user-settable frequency bin widths and the spectra can be saved on the PC.

Clocking and timestamping are realized using a Datum ExacTime GPS Receiver. The 10 MHz GPS signal is used to reference a frequency synthesizer that is operated up to 500 MHz to provide the clock signal on the daughter card. Continuous timestamping of all data points is provided by superposing 1 pps GPS signal to the analog signal at the input of ADCs. Timestamping relative to the UTC is obtained by correlating sampled data with GPS timestamps dumped from the GPS receiver using the RS232 interface.

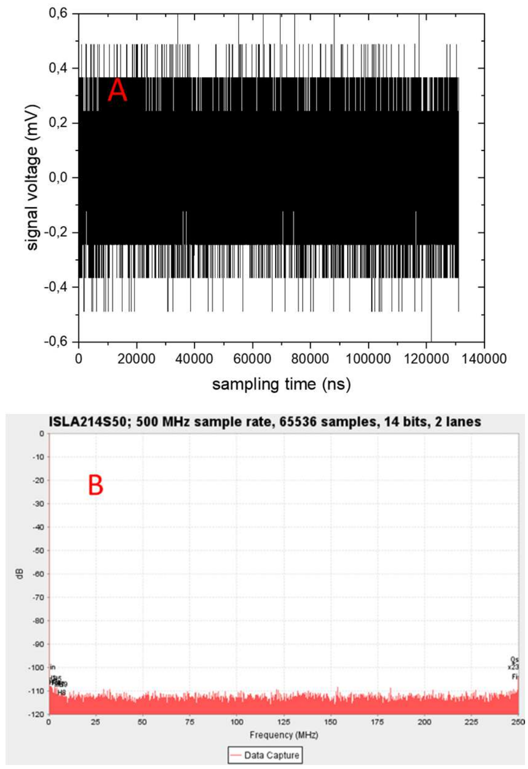


Fig. 3. A. Sampled data points at the limit of the data acquisition system electrical noise. B. FFT post-processing by software.

Fig. 3.A displays a set of $2^{16}$ sampled data points at 500 MSPS sampling speed. There is no electrical input on ADC convertors. Fig. 3.B indicates the FFT spectrum provided by the software with 250 kHz frequency bins, up to the 250 MHz Nyquist frequency. Calibration of the data acquisition system is provided by coupling reference radiofrequency signals to the ADCs. The noise floor of the data acquisition system is measured by -90 dBm up to 250 MHz

## IV. CONCLUSION

This contribution addresses design of a high-speed data acquisition system in a network of laser spectrometers. The setup, based on a differential photodetector and a high-speed ADC evaluation platform, allows recording data points up to 1 Mword with a sampling rate up to 500 MSPS. Clocking and accurate synchronization are driven by signals provided by a GPS receiver. The electrical noise floor in the data acquisition system is at -90 dBm. The application of this setup is for searching fast oscillations of the fundamental constants induced by coupling of an USDM fields to SM particles.


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