# Scattered Light Studies for LISA

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**Abstract**

At the Laboratoire ARTEMIS various experimental and theoretical works are devoted to gravitational waves and their detection by laser interferometry. The ARTEMIS LISA group has implemented an optics set-up where scattered light is injected into an otherwise nominal heterodyne interferometer, in a controlled manner. The resulting perturbation of the heterodyne signals is recorded and analyzed against the characteristics of the injected stray light (injected power, speckle properties, etc.). The goal is to establish a model of the perturbation, and of the noise that results, in the LISA heterodyne phase measurements, due to the presence of coherent scattered light in the instrument.

## 1 Introduction

Laser Interferometer Space Antenna (LISA) is a space based gravitational wave detector. The goal of LISA is to detect gravitational waves through laser interferometery.In order to effectively detect gravitational waves LISA needs to utilize heterodyne interferometery because disturbance from Earth and other planets will impact the length of the arms. This spacecraft will consist of three satellites which will form a Michelson interferometer. These satellites flow a heliocentric orbit.LISA will detect gravitational waves at low frequencies from 0.1 MHz to 100 MHz. When a gravitational wave passes through LISA the length of the arms of the interferometer and the light and the optical path lengths within the interferometer to change. This change shows up as a change in the phase read-out of the interferometer on-board the LISA satellite.

Due to the sensitivity of the interferometer(the target noise floor is 10pm/ rt Hz) unwanted noise can be picked up by the interferometer, and, due to the sensitivity of the interferometer (target noise floor of 10pm/rtHz) even small perturbations can be a problem. This noise affects measurements and distorts gravitational wave detection.

### 1.1 Safety Precautions

The operation of Difflight requires the use of a 1064 nm laser. This is an infrared laser the requires safety precautions. We wore personal protective equipment and Thorlabs LG1 Laser Safety Glasses, Light Green Lenses, 59% Visible Light Transmission.

### 1.2 Stray Light

Stray Light is light in an optical system which was not intended in the design. One usually separates stray light in incoherent stray light (light from the sun, from stars or from lighting systems) and coherent stray light, which can interfere with nominal light. Interference of coherent stray light with nominal light will perturb (shift, or even render unstable) the phase of the nominal light, and so, can add a noise to the readout of the heterodyne interferometers.Establishing a model of perturbation helps LISA better understand the effects of stray light within its optical system. This is particularly true for stray light called scattered light: this light field, generated by a random roughness profile, or by

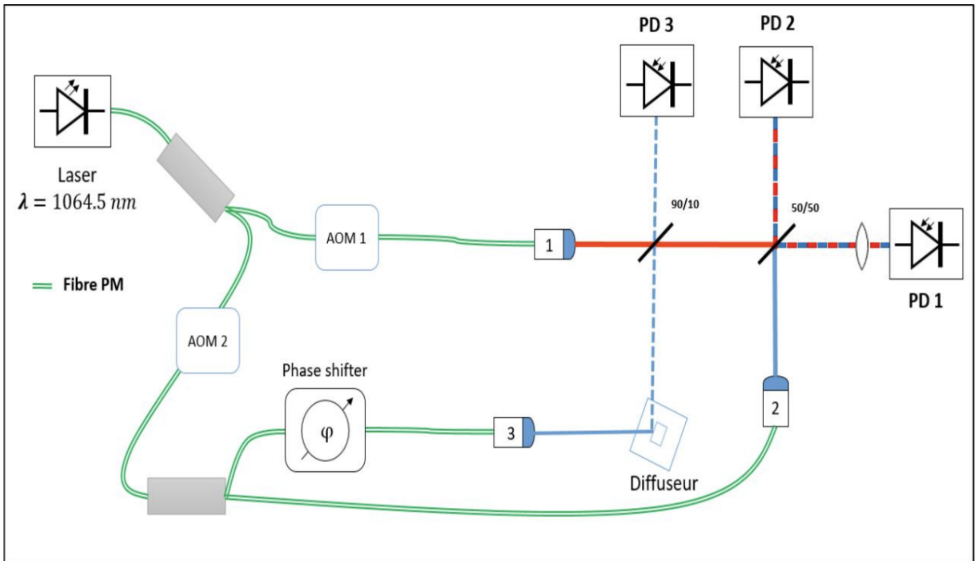


Figure 1: Principle setup of Difflight. Blue lines show the lines with the highest frequency (dotted line: injected stray light). Red lines represent the nominal beam. Double green represent the polarization-maintaining optical fiber or PM fibers

point scatters distributed randomly, is itself a random distribution both in phase and amplitude. This is why a set-up called Difflight, has been constructed to study how coherent scattered light perturbs an otherwise nominal, heterodyne interferometer.

## 2 The Effect of Stray Light in Difflight

Below is the principle setup and the basis of Difflight. Difflight is the optics set up where scattered light is intentionally injected into a nominal heterodyne interferometer. Collimators 1 and 2 generate the beams for the two arms of of the heterodyne interferometer. Collimator 3 deliberately shines light onto a onto a surface which scatters light into the interferometer formed by collimator 1 and collimator 2, the 50/50 beam splitter, and photodiodes PD1 and PD2 (see Fig. 1). This setup allows us to control the amount and of stray light we inject into the interferometer.

Having multiple photodiodes allows us examine the interferometer at multiple points. We can observe stray light from the nominal photodiode which is directly in front of collimator 1. Photodiode 3 allows us to inspect the injection light.

## 3 Setup

### 3.1 Optical Setup

Above is a picture of the internal setup of Difflight. The source of light is the Orion Laser which has a wavelength of 1064.4 nm and power of 24.6 mW. The laser is put through a beam splitter that allows it to be used simultaneously with a separate experiment. We control the light through Polarization-maintaining optical fiber (PM fiber) shown by the double green lines. We use an attenuator at 3 dB. An attenuator is a resistive network designed to weaken the power being supplied by a source. This connects to fiber optic coupler which allows the light to be split into two different paths. Here the split is 90/10. Both PM fibers are connected to Acoustic Optic Modulator (AOM). An AOM controls the optical frequency of a laser beam with an electrical drive signal. This AOM are first connected to the Rigol Waveform generator. With the Waveform generator we can choose at what frequency we would like to set the AOM's at. Here we select a 50 MHz and 49 MHz for AOM2 and AOM1, respectively. This means that arm 1 will be at 49 MHz and arm 2 will be at 50 MHz. Arm 1 is connected to a collimator L1 which collimaters the laser into into a free space beam (in red in Fig. 1). Arm 2 is set through fiber optic coupler again. This split is 75/25 (see Fig. 2). 25% is set through an attenutor at

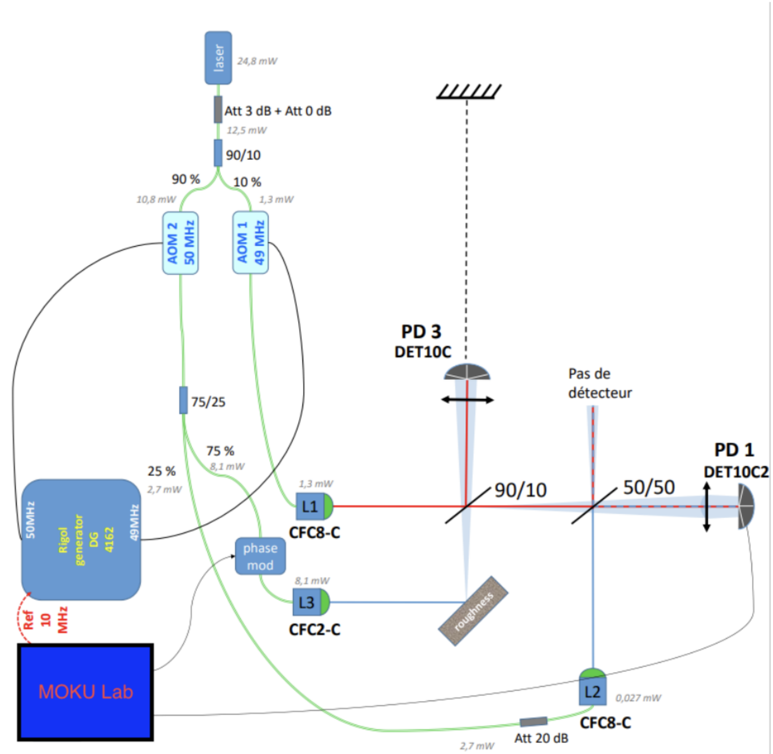


Figure 2: Schematic of Difflight currently.L1 generates arm 1 a,d L2 generates arm 2 of the nominal heterodyne interferometer. L3 generates that beam which is scattered at the scattering surface.

20 dB and is finally collimated at collimator 2. CFC8 and CFC2 are the reference for the collimators. These collimators are adjustable. The 75% is set to a 1.55 um phase modulator and is connected to collimator L3. Phase modulators are used to delay the phase.

Arm 1 directs a beam of light onto a 90/10 beam spiltter of which 90% is sent to photodiode 3 (PD 3) and 10% is sent to a the 50/50 beamsplitter of the nominal heterodyne interferometer. 50 is sent to photodiode 1 and the rest is dumped (PD2 hasn't been set up yet). Arm 2 sends a beam onto the 50/50 beam spiltter. 50 is reflected to photodiode 1 (PD 1). 50 is sent to a beam dump. From L3 a beam of light is sent to a surface which scatters which scatters light onto the 90/10 beam spiltter and then is transmitted to PD3 for the monitoring of the injected stray light fractional amplitude.

The 90/10 beam spiltter creates an injector interferometer which allows stray light to be injected and allows us to measure stray light by observing the size of the beat note on PD 3. PD1 main purpose is measure the nominal signal while PD 3 is used to measure the amount of stray light injected.

## 3.2 Electronic Setup

In order to analyze stray light our electronic set up is crucial. Below is a picture of the electronic Setup that is connected to our internal setup through a series of BNC cables.

Below is picture of our set up. Starting from the top we have a Rigol oscilloscope which assist in showing us which assists in displaying different electrical signals coming from out experiment. Here we can check that the frequency and amplitude of our signal is present and accurate. Below the oscilloscope is the is the Moku lab. The Moku lab is essentially a fast ADC on a hardware FPGA platform that platform that allows you to connect to a tablet or laptop and use any 12 instruments wired into it. We primarily use the lock in amplifer but we found convenient to also use the built-in spectrum analyzer and oscilloscope. We have two Moku labs which can be connected to each other. On the bottom we have our waveform generator which is used to make electrical waveform over a wide range of signals. We have place the waveform generator in a box to reduce the amount of acoustic perturbation to the optics set-up.

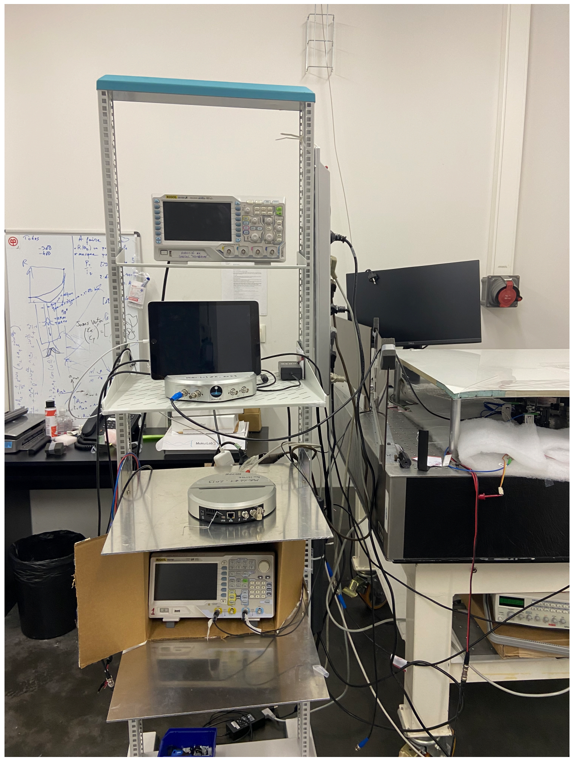

Figure 3: Picture of Difflight electronic setup currently. From top to bottom we have a oscilloscope, iPad which is connected to the Moku Lab unites, and the waveform generator. Not pictured is the amp and the optical bench

Not pictured is our RS function generator which can generate various signals up to 3 MHz. Previously we also had a amplifier attached to the experiment but we move it to the optical bench to reduce the noise pick-up between the amplifier and PD 3.

### 3.3 Demodulation

The primary purpose of the Moku lab was to use its lock-in amplifier. The lock-in amplifiers helps to extract signals with a know carrier wave from noise environments. It can achieve this through the process of demodulation. The signal from the photodiode is numerically multiplied by the reference signal. This passes through a low pass filter which cuts noise at unwanted frequencies. the I +jQ is the demodulated signal where I is in phase and Q has an offset of 90°. The combination of in phase and quadrature components provides provides the phase of the signal: from the interferometer.

$$\phi = arctan(Q/I) \tag{1}$$

The moku lab takes this process of demodulation one step further. Within the Moku lab we can change what the internal local oscillator, the phase shift, the frequency of the low pass filter the gain and the output offset. Moku provides a feature that allows you to examine what the signal looks like after each step. These points are know as "Probe points." You are also able to demodulate two signals at the same time through the use of two different Moku lab using the same display. A picture of this process is below.

### 3.4 Theoretical Signals

One of the first steps to ensure our steps are correct is to find the expected theoretical signals from Difflight. We can do this by using the principle of conservation of energy. First we look at the Fresnel coefficients which tell us the reflection and transmission of light when incident on an interface between different optical media.

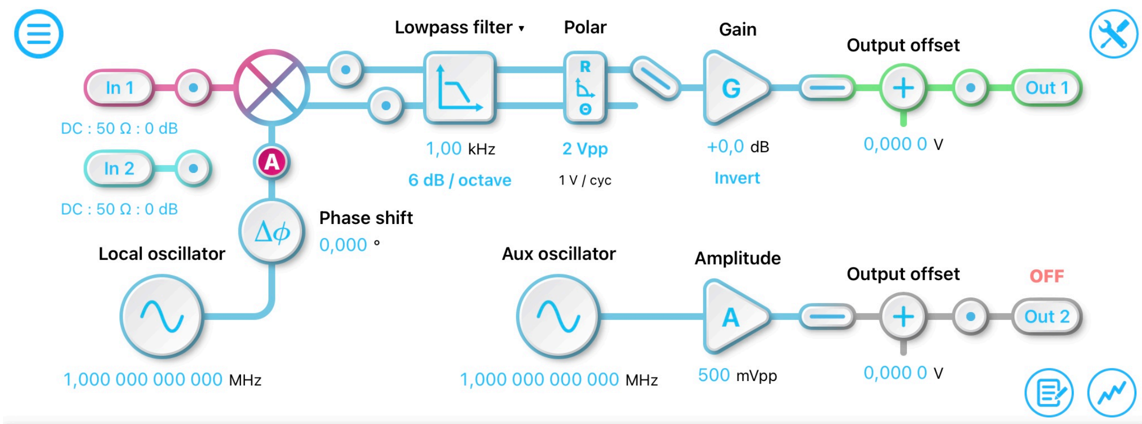


Figure 4: User interface on the iPad for the lockin amplifier within Moku Lab

$$r_{A+},\, r_{B+},\, t_A, t_B > 0$$

The sum of the reflection and power transmission coefficients is 1.

$$r_{A+}^2 + t_A^2 = 1$$
$$r_{B+}^2 + t_B^2 = 1$$

We write need to find the optical amplitude at the outputs of the collimators L1,L2, and L3. The frequency from L3 is arbitrary.

$$\mathring{A}_1 = a_1 e^{j(\omega_1 t + \phi_1)} \tag{2}$$

$$\mathring{A}_2 = a_2 e^{j(\omega_2 t + \phi_2)} \tag{3}$$

$$\mathring{A}_3 = a_3 e^{j(\omega_3 t + \phi_3)} \tag{4}$$

Next we find the sum of the amplitudes on each photodiode

$$_{PD1} =_1 t_A t_B +_3 r_{A_-} r_{B_+} +_2 r_B \tag{5}$$

$$_{PD2} =_1 t_A r_{B_+} +_3 r_{A_-} r_{B_+} +_2 t_B \tag{6}$$

$$_{PD3} =_1 r_{A_+} +_3 t_A \tag{7}$$

Then we find that the intensity on each photodiode is. We need to do detailed calculations for PD 3 because the intensity of PD 1 and PD 2 are essentially the same.

$$\begin{aligned} I_{PD3} &= \left|_{PD3}\overset{*}{_{PD3}}\right|^2 \\ &= \left|\left(a_1 r_{A_+} e^{j(\omega_1 t+\phi_1)} + a_3 t_A e^{j(\omega_3 t+\phi_3)}\right)\left(a_1 r_{A_+} e^{-j(\omega_1 t+\phi_1)} + a_3 t_A e^{-j(\omega_3 t+\phi_3)}\right)\right|^2 \\ &= \left(a_1 r_{A_+}\right)^2 + \left(a_3 t_A\right)^2 + a_1 a_3 t_A r_{A_+} e^{j(\omega_1 t+\phi_1)} e^{-j(\omega_3 t+\phi_3)} + a_1 a_3 t_A r_{A_+} e^{-j(\omega_1 t+\phi_1)} e^{j(\omega_3 t+\phi_3)} \\ &= \left(a_1 r_{A_+}\right)^2 + \left(a_3 t_A\right)^2 + 2 a_1 a_3 t_A r_{A_+} cos\left[\left(\omega_1 - \omega_3\right) t + \phi_1 - \phi_3\right] \end{aligned} \tag{8}$$

Find the resulting intensity on PD 1 and PD 2

$$\begin{aligned} I_{PD1} = \left(a_1 t_A t_B\right)^2 + \left(a_3 r_{A\_} t_B\right)^2 + \left(a_2 r_{B\_}\right)^2 + 2 a_1 a_3 t_A t_B^2 r_{A\_} cos\left[\left(\omega_1 - \omega_3\right) t + \phi_1 - \phi_3\right] \\ + 2 a_1 a_2 t_A t_B r_{B\_} cos\left[\left(\omega_1 - \omega_2\right) t + \phi_1 - \phi_2\right] + 2 a_2 a_3 r_{A\_} r_{B\_} t_B cos\left[\left(\omega_2 - \omega_3\right) t + \phi_2 - \phi_3\right] \end{aligned} \tag{9}$$

$$
\begin{aligned}
I_{PD2} = &\left(a_1 t_A r_{B_+}\right)^2 + \left(a_3 r_{A_-} r_{B_+}\right)^2 + \left(a_2 t_B\right)^2 + 2a_1a_3 t_A r_{B_+}^2 r_{A_-} cos\left[\left(\omega_1 - \omega_3\right)t + \phi_1 - \phi_3\right] \\
&+ 2a_1a_2 t_A r_{B_+} t_B cos\left[\left(\omega_1 - \omega_2\right)t + \phi_1 - \phi_2\right] + 2a_2a_3 r_{A_-} r_{B_+} t_B cos\left[\left(\omega_2 - \omega_3\right)t + \phi_2 - \phi_3\right]
\end{aligned} \tag{10}
$$

To check that energy is conserved in our system we will verify that the sum of the intensity at the output of the collimators is equal to the sum intensities entering the photodiodes.

$$
I_\Sigma = I_1 + I_2 + I_3 = a_1^2 + a_2^2 + a_3^2 \tag{11}
$$

$$
I_{PD} = I_{PD1} + I_{PD2} + I_{PD3} \tag{12}
$$

$$
\begin{aligned}
I_{PD} = &a_1^2\left(t_A^2 t_B^2 + t_A^2 r_{B_+}^2 + r_{A_+}^2\right) + a_3^2\left(r_{A_-}^2 t_B^2 + r_{A_-}^2 r_{B_+}^2 + t_A^2\right) + a_2^2\left(r_{B_-}^2 + t_B^2\right) \\
&+ 2a_1a_3 cos\left[\left(\omega_1 - \omega_2\right)t + \phi_1 - \phi_3\right]\left(t_A r_{A_+} + t_A t_B^2 r_{A_-} + t_A r_{A_-} r_{B_+}^2\right) \\
&+ 2a_1a_2 cos\left[\left(\omega_1 - \omega_2\right)t + \phi_1 - \phi_2\right]\left(t_A r_{B_+} t_B + t_A t_B r_{B_-}\right) \\
&+ 2a_2a_3 cos\left[\left(\omega_2 - \omega_3\right)t + \phi_2 - \phi_3\right]\left(r_{A_-} r_{B_+} t_B + r_{A_-} r_{B_-} t_B\right)
\end{aligned} \tag{13}
$$

Then we factor out the Fresnel Coefficient

$$
\begin{aligned}
I_{PD} = &a_1^2\left(t_A^2\left(t_B^2 + r_{B_+}^2\right) + r_{A_+}^2\right) + a_3^2\left(r_{A_-}^2\left(t_B^2 + r_{B_+}^2\right) + t_A^2\right) + a_2^2\left(r_{B_-}^2 + t_B^2\right) \\
&+ 2a_1a_3 cos\left[\left(\omega_1 - \omega_3\right)t + \phi_1 - \phi_3\right] t_A\left(r_{A_+} + r_{A_-}\left(t_B^2 + r_{B_+}^2\right)\right) \\
&+ 2a_1a_2 cos\left[\left(\omega_1 - \omega_2\right)t + \phi_1 - \phi_2\right] t_A t_B\left(r_{B_+} + r_{B_-}\right) \\
&+ 2a_2a_3 cos\left[\left(\omega_2 - \omega_3\right)t + \phi_2 - \phi_3\right] r_{A_-} t_B\left(r_{B_+} + r_{B_-}\right)
\end{aligned} \tag{14}
$$

Now we can simplify our previous equations. We find the terms cancel out while the nominal terms are multiplied by one. In the end, we find our desired equation.

$$
I_{PD} = a_1^2 + a_2^2 + a_3^2 = I_\Sigma \tag{15}
$$

Now we need to check if it is possible to get rid of stray light by subtracting the intensity

$$
\begin{aligned}
I_{PD1} - I_{PD2} = &a_1^2 t_A^2\left(t_B^2 - r_{B_+}^2\right) + a_3^2 r_{A_-}^2\left(t_B^2 - r_{B_+}^2\right) + a_2^2\left(r_{B_-}^2 - t_B^2\right) \\
&+ 2a_1a_3 cos\left[\left(\omega_1 - \omega_3\right)t + \phi_1 - \phi_3\right] t_A r_{A_-}\left(t_B^2 - r_{B_+}^2\right) \\
&+ 2a_1a_2 cos\left[\left(\omega_1 - \omega_2\right)t + \phi_1 - \phi_2\right] t_A t_B\left(r_{B_-} - r_{B_+}\right) \\
&+ 2a_2a_3 cos\left[\left(\omega_2 - \omega_3\right)t + \phi_2 - \phi_3\right] r_{A_-} t_B\left(r_{B_-} - r_{B_+}\right)
\end{aligned} \tag{16}
$$

50/50 beam splitter splits everything evenly

$$
t_B^2 = r_{B_+}^2 \tag{17}
$$

$$
t_B^2 = r_{B_+}^2 \tag{18}
$$

Then we apply the relation between the Frensel coefficients

$$
\begin{aligned}
I_{PD1} - I_{PD2} = &-4a_1a_2 t_A t_B r_{B_+} cos\left[\left(\omega_1 - \omega_2\right)t + \phi_1 - \phi_2\right] \\
&+ 4a_2a_3 r_{A_+} t_B r_{B_+} cos\left[\left(\omega_2 - \omega_3\right)t + \phi_2 - \phi_3\right]
\end{aligned} \tag{19}
$$

$$
\begin{aligned}
I_{PD2} - I_{PD1} = &4a_1a_2 cos\left[\left(\omega_1 - \omega_2\right)t + \phi_1 - \phi_2\right] t_A t_B r_{B_+} \\
&- 4a_2a_3 cos\left[\left(\omega_2 - \omega_3\right)t + \phi_2 - \phi_3\right] r_{A_+} t_B r_{B_+}
\end{aligned} \tag{20}
$$

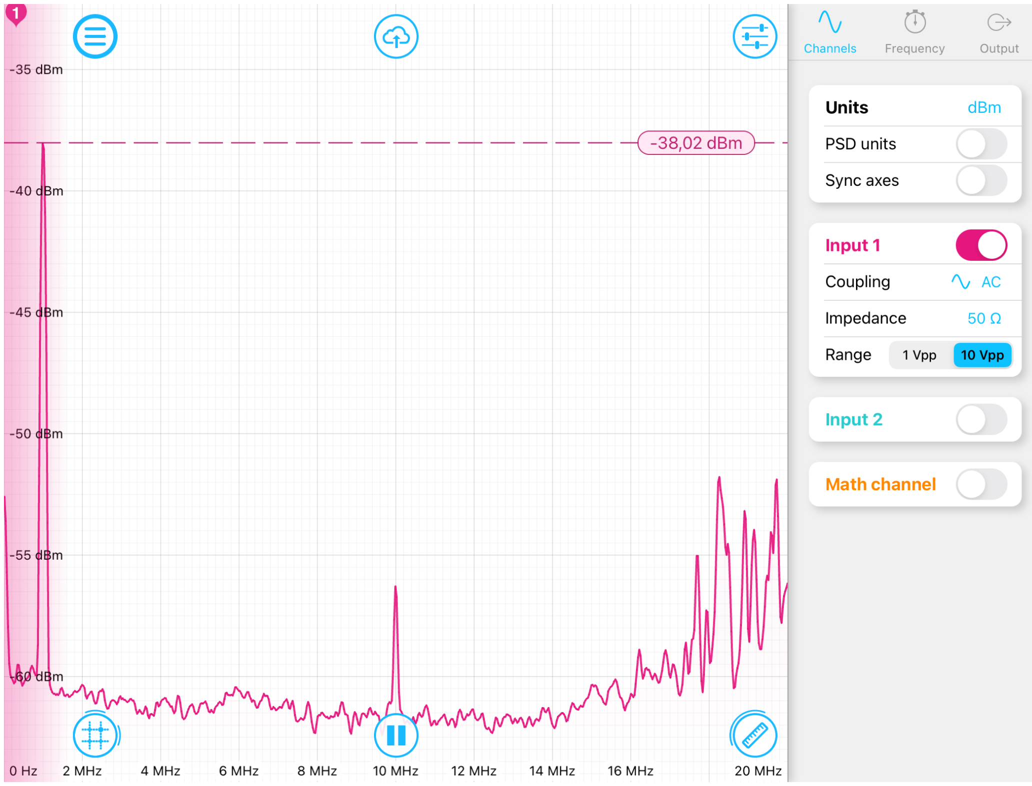


Figure 5: Spectrum Analyzer Screenshot from Moku Lab. Here we observe peak at 1MHz. This peak is from the nominal photodiode. No beams were masked at this time

# 4 Results

## 4.1 Optical Interference

We observe a spectrum of optical interference at 1MHz for both the nominal photodiode and the injection photodiode. When looking at the spectrum analyzer we observed a peak at 1 MHz. In order to determine if this was optical interference or interference from a third party source we masked stray light. The peak at 1 MHz disappears. Therefore we know that this peak is caused by scattered light from L3. A picture of this observed peak will be shown down below.

Investigating this optical interference in depth we observed that this peak has more qualities. We see that both the spectrum of the injection signal and the spectrum og the nominal signal contain side bands. Side bands are bands of frequency that are either higher or lower then the carrier frequency.

First looking at the injection signal we see that without phase modulation that spectrum is affected by noise and become difficult to read.Second looking at the nominal signal we see that some side bands are due to acoustic pickup. We can verify the validity of the side bands by measuring the power and frequency.


Figure 6: Spectrum Analyzer Screenshot from Moku Lab. Here we observe peak at 1MHz has disappeared . This peak is from the nominal photodiode. Stray light was masked at this time

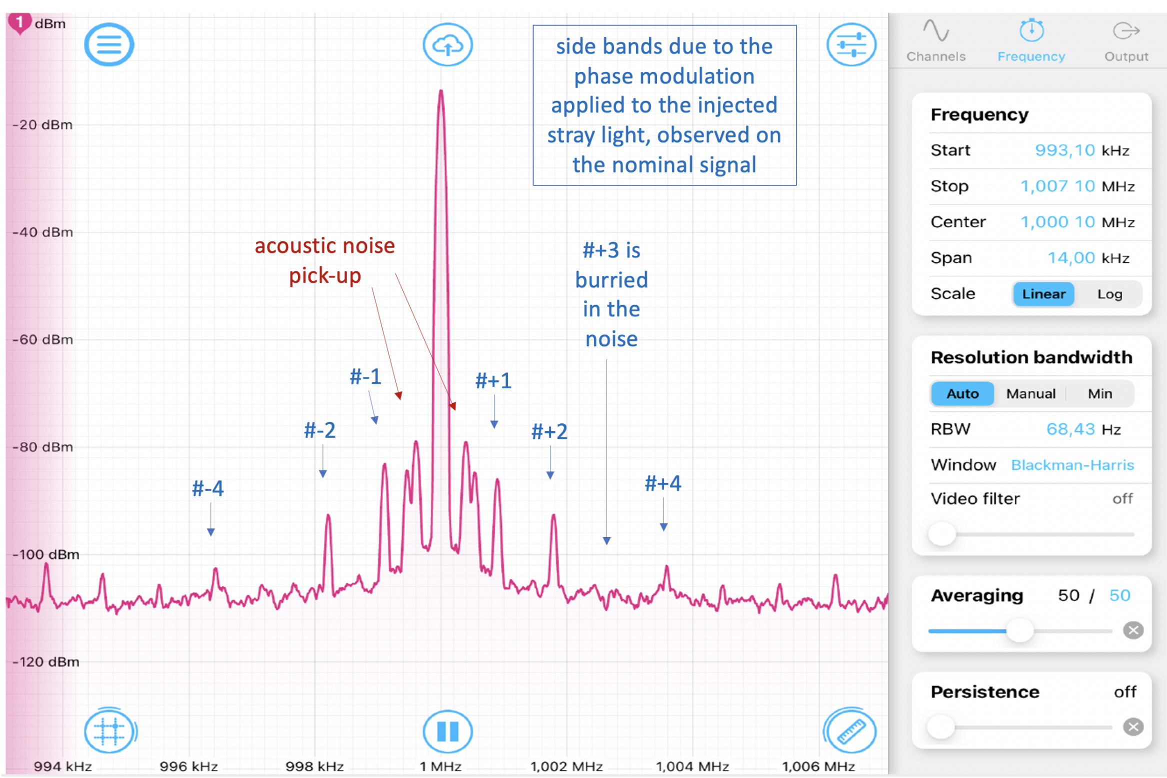


Figure 7: Here we see the side bands from the 1 MHz from the nominal photodiode.

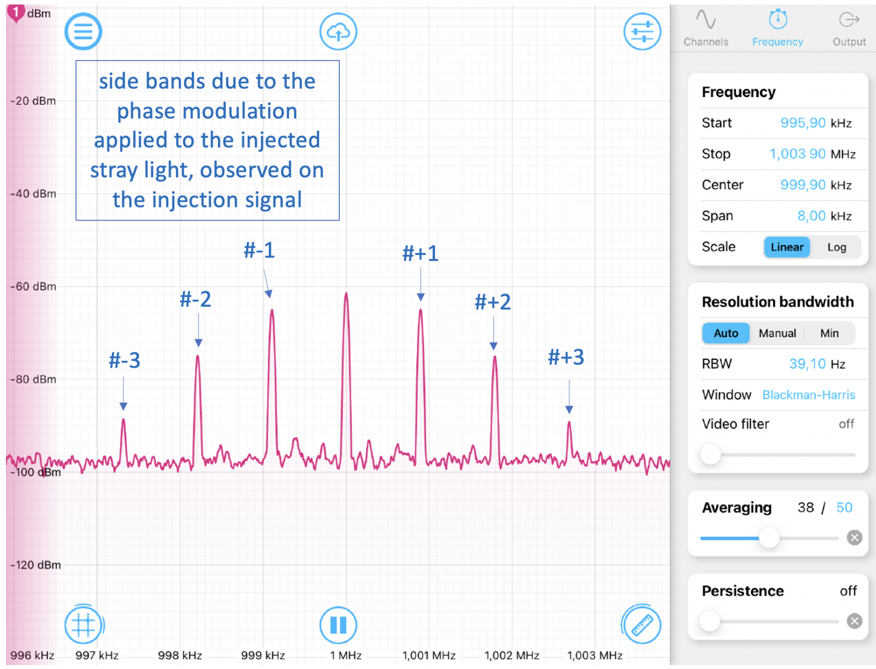


Figure 8: Here we see the side bands from the 1 MHz from the injection photodiode. In

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