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Noise Performance Optimization of a Fast Wavelength Calibration Algorithm for OSAs

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***Abstract*—**A new fast correlation algorithm for calibrating the wavelength of Optical Spectrum Analyzers (OSAs) was introduced in [1]. The minima of acetylene gas spectra were measured and correlated with saved theoretical data [2]. So it is possible to find the correct wavelength calibration data using a noisy reference spectrum. First tests showed good algorithmic performance for gas line spectra with high noise. In this article extensive performance tests were made to validate the noise resistance of this algorithm. The filter and correlation parameters of the algorithm were optimized for improved noise performance. With these parameters the performance of this wavelength calibration was simulated to predict the resulting wavelength error in real OSA systems. Long term simulations were made to evaluate the performance of the algorithm over the lifetime of a real OSA.

***Keywords*—**correlation, gas reference, optical spectrum analyzer, wavelength calibration

I. Introduction

In modern telecommunication systems Optical Spectrum Analyzers are essential to characterize the transmission channels with respect to wavelengths and powers. This is necessary during installation of new transmission systems and after detecting a malfunction during system operation.

With channel spacing in modern Dense Wavelength Division Multiplexing (DWDM) systems down to 12.5 GHz [3] it is essential for Optical Spectrum Analyzers to use a built-in precise absolute wavelength reference which recalibrates the OSA during operation.

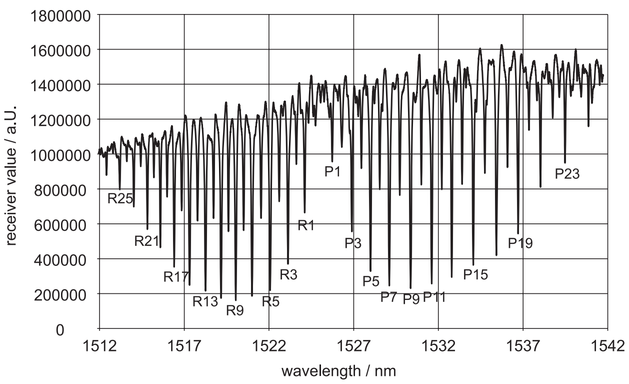

Fig. 1 Acetylene reference spectrum

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The most commonly used reference contains a gas which absorbs small wavelength bands due to molecular resonance. Acetylene $^{12}C_2H_2$ has strong absorption lines in the 1550 nm wavelength region and is therefore often used for commercial OSAs [4][5]. Figure 1 shows a measured gas line spectrum with negligible noise which was used as the basis spectrum for all algorithm performance simulations in this article.

The main challenge for wavelength calibration using a gas absorption spectrum is getting a spectrum with low noise. This is necessary with calibration algorithms which search the minima of the spectrum, counting them and assign them to theoretical wavelength values. Finding a noise dip instead of a gas line leads to a wrong assignment between theoretical wavelength data and measured minima. This leads to a wrong match and therefore a large wavelength error.

The main noise source in the wavelength reference path of an OSA is the first stage of the receiver amplifier with the thermal noise of the resistors and shot noise of the transistors. Therefore high optical power is necessary which leads to high hardware costs of the instrument.

In [1] it was shown that it is possible to use a reference spectrum with high noise for wavelength calibration. The block diagram of this calibration algorithm is shown in figure 2. The noise of the measured spectrum is reduced with a Savitzky-Golay filter [6]. The extreme values are extracted and correlated with the stored theoretical minima to find the wavelength calibration parameters.

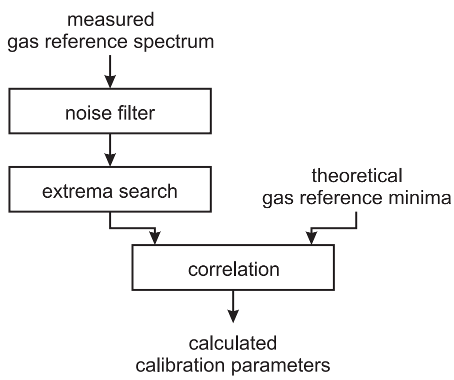

Fig. 2 Block diagram of wavelength calibration algorithm

So it is possible to calculate the wavelength calibration parameters using an Intel Celeron Processor with 1.5 GHz within 52 ms.

In this paper the in [1] developed wavelength calibration algorithm is tested for wavelength accuracy with different noise levels. The correlation parameters are optimized for optimum performance at high noise levels. Predictions are made for the resulting calibration error in real OSA systems.

In Section II Monte Carlo simulations are done for checking the noise robustness of the wavelength calibration algorithm with not optimized algorithm parameters. The optimization of the algorithm is shown in Section III. In Section IV long term simulations of the algorithm are made to test the algorithm behavior over the lifetime of an OSA. The final Section V summarizes the work and the results.

II. Noise Performance Simulation

A. Simulation method

For the algorithm performance simulation the nearly noise free gas reference spectrum of figure 1 is added to computer generated noise spectra with nearly gaussian amplitude distribution (fig. 3). The wavelength calibration algorithm extracts the calibration parameters which are compared with stored values of the noise-free spectrum. The differences between the theoretical calibration values and the calculated calibration parameters are calculated to simulate the wavelength errors for certain characteristic wavelengths.

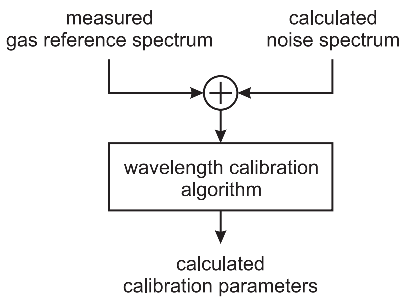

Fig. 3 Block diagram of noise performance simulation

The wavelength calibration parameters for the slope "a" and the offset "b" are used to calculate the corrected wavelength λ_{corr} from the measured wavelength λ_{meas}.

$$\lambda_{corr} = a \cdot \lambda_{meas} + b \tag{1}$$

The noise simulation is done from the electrical view in the OSA. The photodiode converts the optical power from the optical fiber to a proportional electrical current. The main noise in the spectrum is electrical noise from the first amplifier stage. The whole electrical current $I_{Sum}(\lambda)$ is the sum of the signal current $I_{Sig}(\lambda)$ and noise current $I_N(\lambda)$.

$$I_{Sum}(\lambda) = I_{Sig}(\lambda) + I_N(\lambda) \tag{2}$$

The electrical signal to noise ratio SNR_{el} is calculated as the sum of the power density over the wavelength which is proportional to the squared current.

$$SNR_{el} = 10\text{dB} \cdot \log_{10}\left(\frac{\sum_{\lambda} I_{Sig}^2(\lambda)}{\sum_{\lambda} I_N^2(\lambda)}\right) \tag{3}$$

Because the optical power is proportional to the electrical current

$$P_{opt} \sim I_{Sig} \tag{4}$$

the SNR_{el} in (3) can be transformed to the optical domain:

$$SNR_{opt} = OSNR = 5\text{dB} \cdot \log_{10}\left(\frac{\sum_{\lambda} I_{Sig}^2(\lambda)}{\sum_{\lambda} I_N^2(\lambda)}\right) \tag{5}$$

This optical signal to noise ratio OSNR is necessary for developing the optical system of the OSA. Therefore all simulation results are calculated with OSNR.

B. Allowed deviation of calibration parameters

For a detailed error analysis of the calculated wavelength calibration parameters in equation (1) it is not sufficient to do a statistical analysis with average value and standard deviation. It is necessary to do the error analysis with respect to the application of the algorithm in an Optical Spectrum Analyzer.

Most wavelength division multiplexing (WDM) transmission systems work within the C-band which is between 1530 nm and 1565 nm wavelength. Therefore it is most interesting to calculate the wavelength error within this wavelength region.

The secondary interesting wavelength area is the L-band between 1565 nm and 1625 nm which is used by some transmission system to increase the capacity.

When considering ITU-T G694.1 [3] with a channel spacing down to 12.5 GHz it is necessary to have an OSA with an absolute wavelength error less than ±20 pm which equals an error of 20% of the channel spacing. In high performance applications an absolute wavelength error of less than ±10 pm is desirable.

The following simulations and optimizations of the wavelength correlation algorithm are done to achieve this goal using a noisy reference spectrum.

C. Simulation results

First simulations are done with the not optimized algorithm which was developed in [1]. These show the behavior of the algorithm at different noise levels and give hints for optimizations.

For an OSNR of 11.37 dB 100,000 simulations are calculated and the extracted calibration parameters "a" and "b" (see equation 1) are plotted as histograms.

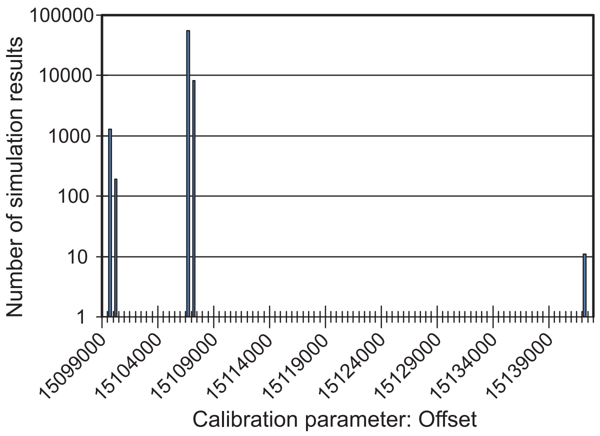

Fig. 4 Histogram of calibration parameter: Offset b

In figure 4 the histogram of the offset parameter "b" is shown. On the abscissa the calculated offset with a unit of 0.1 pm is depicted and at the ordinate the number of simulation results is shown in a logarithmic scale. The distribution of the offset is non-gaussian with the absolute maximum within two depicted intervals at the theoretically correct offset value.

Two side maxima at lower and higher values of "b" are seen. These result from a wrong assignment between the theoretical minima and the calculated minima out of the measured spectrum due to noise. Between the absolute maximum and the two side maxima in figure 4 no other calibration values were found.

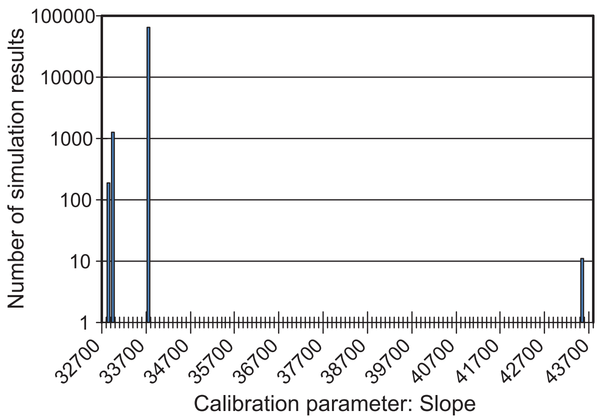

Fig. 5 Histogram of calibration parameter: Slope a

In figure 5 the histogram shows the calibration parameter "a" which is the slope of the linear calibration function. On the abscissa there is the slope parameter with a unit of 10^{-4} pm per measurement point. On the ordinate the number of results is shown in a logarithmic scale. The distribution of results is similar to the distribution if figure 4 with two side maxima at lower and higher values. These result from the match of the theoretical minima with wrong measured minima due to noise influence. Between the main maximum and the two side maxima no other parameter values were calculated.

These side maxima occur when the calibration algorithm finds a different best match between theoretical wavelength minima and measured minima with added noise. Therefore it is necessary for the optimization of the calibration algorithm to improve the noise filter and the weight function of the matching algorithm to reduce the number of found wrong matches.

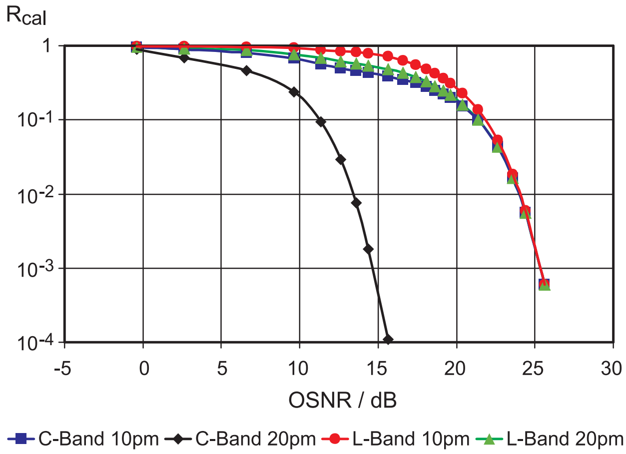

Fig. 6 Wrong wavelength calibration rates in C-Band and L-Band with different OSNRs

In figure 6 the wrong wavelength calibration rates of the Monte-Carlo simulations with different OSNRs are shown. For each OSNR value 100,000 simulations are done. The abscissa shows the OSNR in dB between the ideal gas spectrum and the noise (see equation 5). The ordinate depicts the ratio of wrong calibrations in a logarithmic scale.

The ratio of wrong calibrations R_{cal} is calculated as:

$$R_{cal} = \frac{\text{Number of wrong calibrations}}{\text{Number of calibrations}} \tag{6}$$

The four curves in figure 6 show the ratio of wrong calibrations for allowed wavelength tolerances of ±10 pm and ±20 pm for the C-Band and L-Band regions.

From the curves we see the necessary OSNR between the ideal gas spectrum and the noise for a given wrong calibration ratio. The curve with ±20 pm C-Band wavelength tolerance shows the lowest necessary OSNR for a given wrong calibration ratio.

The three other curves in figure 6 (±10 pm C-Band, ±10 pm L-Band, ±20 pm L-Band) have very similar behaviors with an approximately 10 dB higher OSNR for an identical wrong calibration rate like the ±20 pm C-Band curve.

III. Algorithm Optimization

For the optimization of the wavelength correlation algorithm shown in figure 2 it is assumed that the optimization of the filter function and the optimization of the correlation algorithm can be done independently.

First the weight parameters of the decision algorithm are optimized and during the second step the noise filter width is optimized.

A. Decision parameter optimization

In the first part of the decision algorithm the minima of the measured spectrum are detected with relative depth and position. These found minima positions are matched to the theoretical wavelengths with the wavelength parameters a and b in equation (1).

The differences between the theoretical minima and the measured minima are calculated regarding to wavelength and relative depth. Depth and wavelength differences are weighted and the minimal sum of these differences is the best match. The corresponding wavelength parameters "a" and "b" are the calibration values.

The weight of the wavelength error and the depth error for the calculation of the deviation minimum can be adjusted within the algorithm to a defined ratio. In this parameter optimization step the optimal ratio is calculated for a minimal wrong calibration rate of the algorithm.

In figure 7 shows the wrong calibration rates on the ordinate for different position to depth weight ratios on the abscissa. The OSNR for all calculations is constant at 15.63 dB. The major change of the wrong calibration rate can be seen at a maximum wavelength error of ±20 pm in the C-Band. For a position to depth weight ratio of two or more the wrong calibration rate decreases by a factor of 10^3 compared to lower position to depth weights. For the other wavelength errors in C-Band and L-Band the wrong calibration rate is nearly constant independent of the position to depth weight ratio.

For the first calculations of the wrong calibration rates (shown in figure 6) the position to depth ratio was chosen 2. Figure 7 shows that this value gives optimal results and therefore it is retained for future calculations and optimizations.

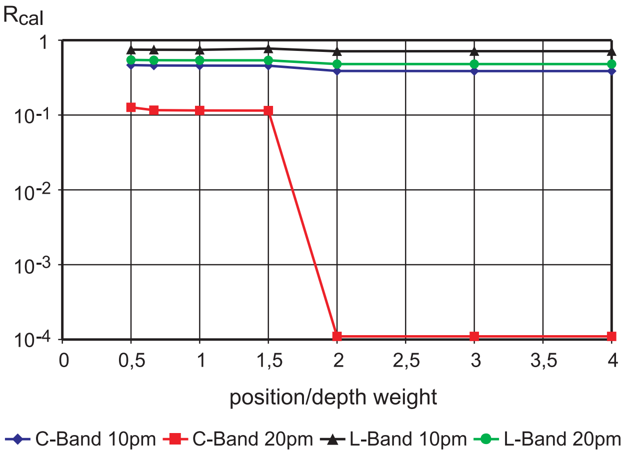

Fig. 7 Wrong wavelength calibration rates in C-Band and L-Band with different position to depth weight ratios

B. Filter optimization

The measured optical spectrum for the wavelength calibration is first filtered with a Savitzky-Golay filter (see figure 2) before the minima are searched and the correlation is done.

For the calculation of the first wrong calibration rates in figure 6 a filter width of 61 points was estimated which is approximately equal to the width of the deep gas line minima in the wavelength reference spectrum.

During this optimization the width of the filter was changed and the wrong calibration rates for different filters were estimated.

Figure 8 shows the logarithmic wrong calibration rate on the ordinate with the OSNR on the abscissa for different filter widths. The curves show the maximum allowed wavelength error is ±10pm in the C-Band for different filter width. This is an important calibration parameter for commercial Optical Spectrum Analyzers because most data sheet specs specify this parameter.

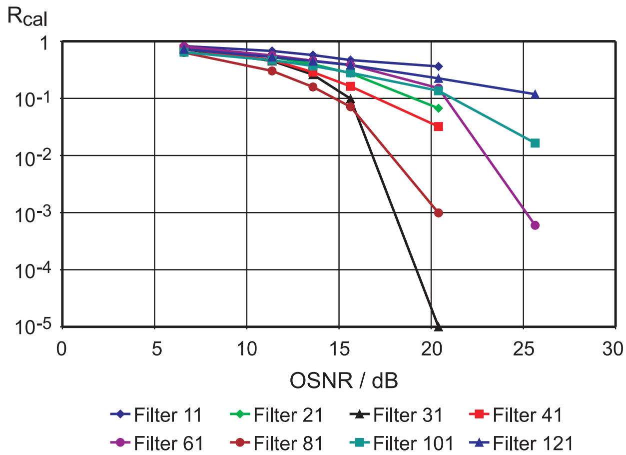

Fig. 8 Wrong wavelength calibration rates for 10pm error in C-Band

Figure 9 shows the logarithmic wrong calibration rates on the ordinate for different OSNRs on the abscissa. The curves show the different filter widths (similar to figure 8) for a maximum wavelength error of ±20 pm in the L-Band which is also an interesting parameter for real OSA systems.

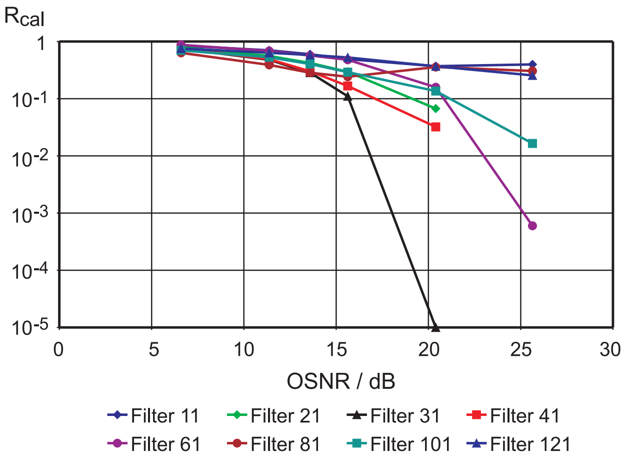

Fig. 9 Wrong wavelength calibration rates for 20pm error in L-Band

The best results in figure 8 and figure 9 are for a 31 point wide filter. The wrong calibration rates at an OSNR of 20 dB are 10^2 to 10^4 lower than for all other simulated filter widths. This shows a big improvement compared to the arbitrary chosen initial filter width and for the rest of the simulations this new filter width is chosen.

IV. Long Term Calibration Simulation

In real OSAs a practically error-free operation is necessary to give reliable wavelength results to the user. Therefore the OSNR must be chosen so that practically no wrong wavelength calibration occurs.

On the other hand a low necessary OSNR of the reference spectrum gives cost advantages for the vendor because of cheaper component usage.

In a real OSA the wavelength calibration will be made as soon as the risk of a wavelength deviation due to environmental changes occurs. The thermal time constant of an OSA optic block is about 30…60 minutes. Therefore a recalibration of the wavelength every ten minutes suffices.

The life time of a high quality OSA should be ten years non-stop operation. During this time approximately 525,600 calibrations are made when assuming a ten minutes recalibration interval.

When simulating the wavelength errors over the whole lifetime the 100,000 Monte-Carlo simulations which are done for optimizations are not sufficient. Therefore long term simulations with the optimized algorithm parameters are done the estimate the necessary OSNR for error-free operation.

For each OSNR value 2 million simulations were made to obtain simulation data far beyond the practical lifetime of a real OSA. If the number of wrong calibrations for an OSNR value was too low for an estimation of the wrong calibration rate the number of simulations was increased to 10 million. So it is possible to simulate much beyond the whole lifetime of a real OSA.

Table I shows the OSNR values where the simulations were made, the number of simulations for each OSNR value and the maximal occurred wavelength deviation in the C-band and L-band during the simulation.

For OSNR values 17.39 dB to 20.41 dB the calibration algorithm found in the worst case simulations a wrong match between the theoretical minima and measured minima due to noise. This leads to a wavelength error of about 2 nm in the C-band and 3.5 nm in the L-band. This is a wavelength error which is not tolerable in real OSA systems.

For an OSNR of 21.08 dB or higher the number of wrong calibration drastically decreases therefore the number of simulations were increased to get a larger number of wrong calibrations. The maximum wavelength deviation is drastically reduced which shows that the right matches between the theoretical and measured minima are found in each calibration. The resulting wavelength deviation is due to noise error.

For an OSNR of 22.17 dB no wrong calibration is found at 10 million simulations which is an error free wavelength calibration over the whole lifetime of the OSA.

TABLE I
Results of Long Term Wavelength Calibration Simulation

OSNR	Number of simulations	Maximum wavelength deviation C-band	Maximum wavelength deviation L-band
17.39 dB	2,000,000	2.0358 nm	3.5148 nm
18.65 dB	2,000,000	2.0186 nm	3.4614 nm
19.62 dB	2,000,000	2.0181 nm	3.4614 nm
20.41 dB	2,000,000	2.0181 nm	3.4614 nm
21.08 dB	10,000,000	14.6 pm	39.6 pm
21.66 dB	10,000,000	14.6 pm	39.6 pm
22.17 dB	10,000,000	1.7 pm	5.2 pm

Figure 10 shows the long term simulation results with the OSNR on the abscissa and the logarithmic wrong calibration rate on the ordinate. The graphs with the wrong calibration rates for a ±10 pm C-band error, ±10 pm L-band error and ±20 pm L-band error are nearly identical.

The polynomial regression which matches these wrong calibration rates is:

$$R_{cal} = 10^{-0.1467 \cdot OSNR^2 + 4.4809 \cdot OSNR - 35.228} \quad (7)$$

For an OSNR more than 21 dB the number of wrong calibrations found in the long term simulation is very low so the deviation between the measured curves in figure 10 and equation (7) increases.

During the 10 million simulations with an OSNR of 22.17 dB the maximum wavelength deviation was only some pm (see Table I) and no wrong wavelength calibration was found. Therefore it is shown that the wavelength calibration algorithm gives correct results and no error floor is detected.

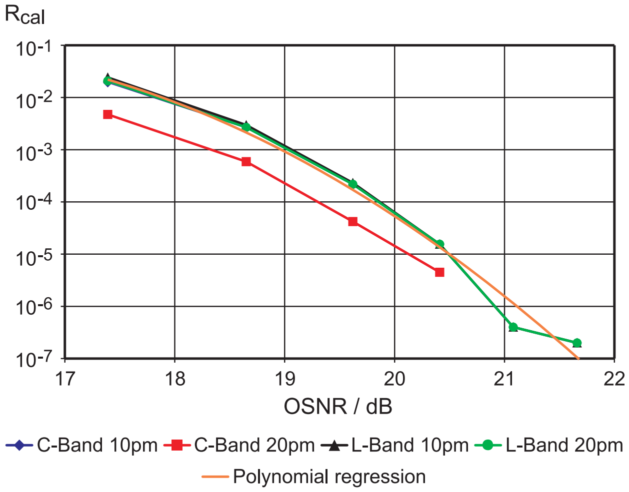

Fig. 10 Wrong wavelength calibration rates with long term simulation

V. Results

The wavelength calibration algorithm which was developed in [1] is optimized regarding to a minimal wrong calibration rate.

The main optimization is made by optimizing the filter width which leads to an improvement of the wrong calibration rates of up to 10^3 at identical OSNRs. This can be seen when comparing the curves with the wrong calibration rates of figure 6 and figure 10.

For an OSNR of 22.17 dB 10 million wavelength calibration simulations were done without an error. This number of simulations is about twenty times the expected lifetime of a real OSA. No error floor of the wavelength calibration was found during the simulations.

Acknowledgment

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