1. Introduction

This document will endeavor to explain the data processing chains for both full spectrum and peak detection dataset in the x55 Hyperion, with a focus on loss sensitivity for both.

2. Explanation

2.1. Full spectrum and peak detection together

As detailed in technical note 1360, the x55 Hyperion platform captures full optical spectrum at the 1kHz scan rate that is used for programmable on-board hardware peak detection. Each 1 ms full spectrum trace is fed into that PD circuitry on each 1 ms scan in order to yield repeatable, accurate sensor peak or valley measurements at the full 1 kHz rate.

As a much-reduced dataset, the peak values of the sensors can be streamed from the instrument to a client computer over standard Ethernet bandwidth capabilities. The full spectrum signal, on the other hand, consists of far too many data points at far too high a rate to ever successfully be transferred over standard available networking protocols.

As such, there is opportunity to do some averaging on the full spectrum data sets within the interrogator, prior to transmitting the data via Ethernet. As a result of this averaging, the signal to noise of the full spectrum is significantly improved over that of a single 1kHz acquisition, leading to enhanced measurements of spectrum at a lower optical power, albeit at a much lower acquisition rate (~10 Hz) as compared to the single acquisition peak data (~ 1kHz).

The image of figure 1 shows the simultaneous peak data (red) and full spectrum (blue) traces from a 16 FBG array as measured by a 1 kHz si255 Hyperion interrogator. In this image, the peak data is acquired from a single 1ms scan and transmitted at a 1kHz. The full spectrum data is collected and averaged from 25 acquisitions and transmitted at a much lower data rate of ~10 Hz. This image is representative of what the user would see from the measurement in a standard mode of operation.

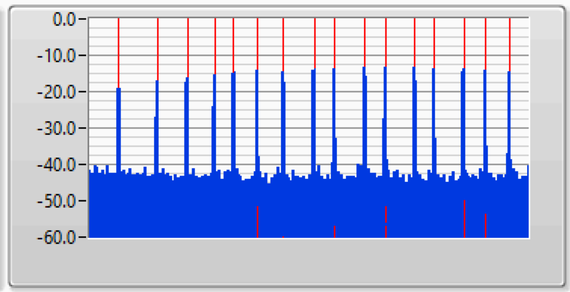


Figure 1. Combined signals from 1 kHz peak detection (red) and 10 Hz averaged full spectrum (blue)

The figure 2 image shows a zoomed view of a single FBG from that 16 FBG array, amplified to show the spectral detail of the FBG as seen in the power-calibrated, averaged full spectrum data. Centered here at 1556nm, this image shows good spectral detail of the FBG below 40 dBm and as low as -55 dBm.

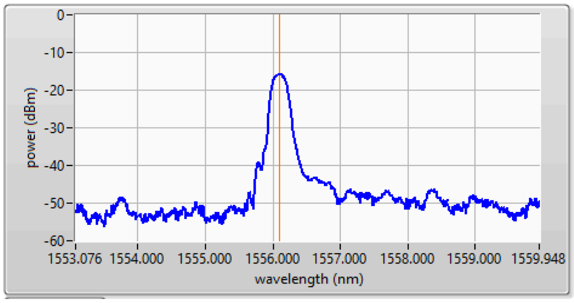


Figure 2. Zoomed view of figure 1 about the 1556 nm FBG.

However, all of this spectral information and dynamic range is not present in each 1 ms single acquisition. Note the following image of figure 3, which shows the actual raw signal (both power and wavelength uncalibrated) that is collected on each 1 ms scan.

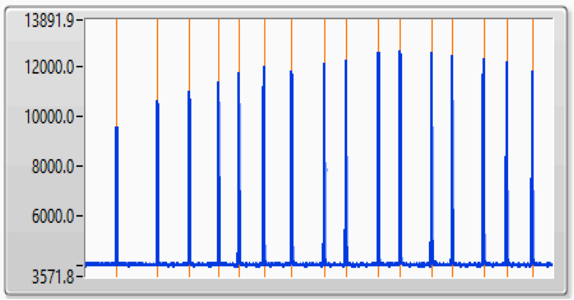


Figure 3. Single 1kHz uncalibrated raw data trace.

This image is the actual data that is collected by the system on each sweep and fed into the internal peak detection algorithm, which functions as detailed in TN 1360.

2.2. From full spectrum to peak data

The next series of images shows how this raw data signal is processed to yield the 1kHz peak data. In these images there are key things to note to better understand the behaviors of the si255 peak detection and full spectrum data processing.

The top left image of figure 4 is a zoomed view of the same 1556 nm FBG highlighted in Figure 2. In this view, however, the signal is still uncalibrated in both wavelength and power (as is all high speed data fed into the PD algorithm. Note how low the short wavelength side mode of the FBG signal appears in the top left trace (uncalibrated for power) as compared to the power calibrated post-processed image of the same FBG on the upper right. The difference in raw and power calibrated traces shows the effects of operating in a near-linear region of the photodiode receivers and amplifier circuit, a feature which offers good dynamic range an time response, but presents data to the peak detection circuitry with a nearly linear representation of the reflection spectrum of the FBG.

The top right image is calibrated for power for illustration purposes here, though only in simulation, as power calibration is not part of the real-time FPGA based peak detection algorithm. Even so, note how when a single acquired data set is power calibrated, the noise floor and degree of signal noise is much greater than when compared to the averaged full spectrum trace of the same 1556 nm FBG, as seen in figure 2. Indeed, this is the crux of the understanding x55 Hyperion behavior. A full spectral raw data trace is limited in its signal to noise and is largely linear in its response. That raw, linear signal is fed to to the real-time PD algorithm, which can track the peak instantaneously down to its single acquisition noise limit. Multiple raw signals are then power calibrated, averaged, and presented to the user as a calibrate full spectrum trace (the blue trace of Figures 2) showing a greatly enhanced spectral representation for low speed processing relative to the 1kHz raw signals on which internal PD is performed.

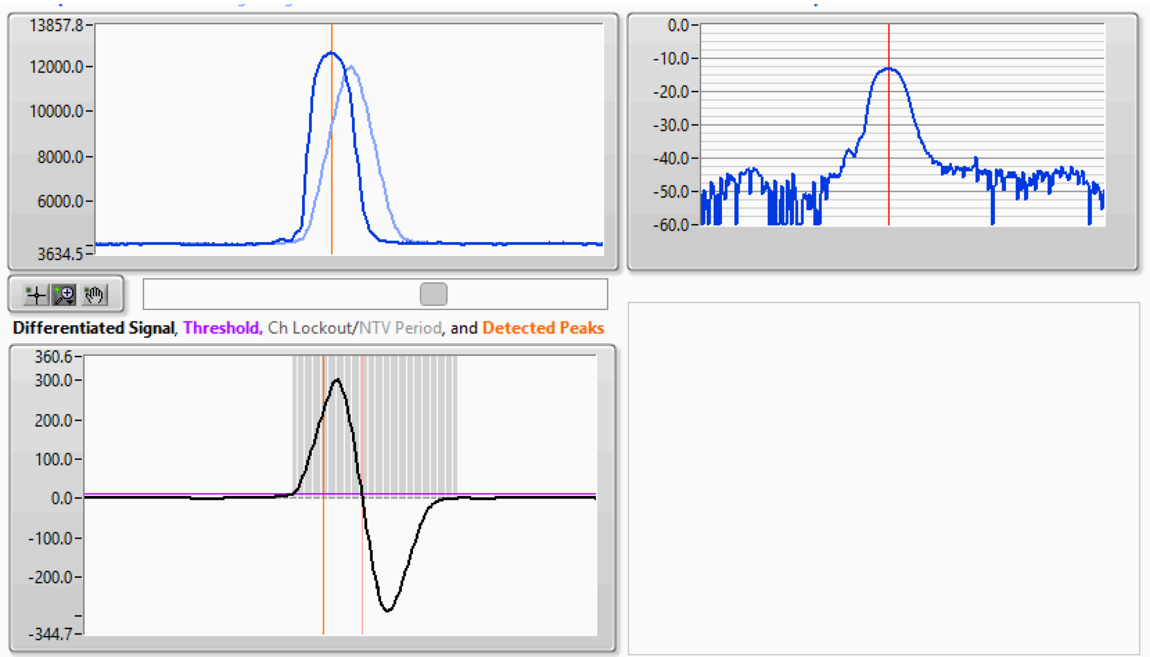
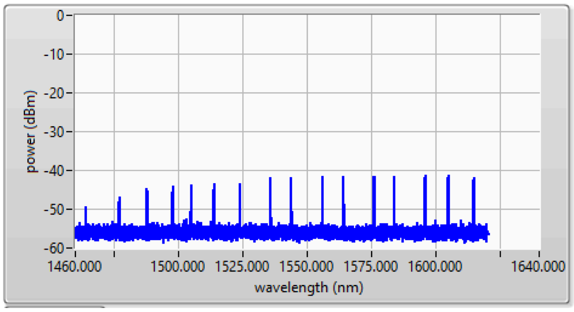


Figure 4. Top left is a the raw, uncalibrated (nearly linear) full spectrum trace. Top right is a simulated trace of power scaled 1kHz internal raw full spectrum. Bottom left is the differentiated peak signal used to determine FBG peak location.
To then illustrate what happens when appreciable loss is added to the system, consider the following series of images.

Figures 5 and 6 shows the same 16 FBG array, in full range and 1556 nm zoomed views, respectively, this time with the addition of ~28 dB of loss. As with Figures 1 and 2, these calibrated full spectrum traces carry the benefit of on-board spectral averaging to reduce instantaneous noise and enhance the dynamic range of the full spectrum measurement. It is precisely these views that can cause user confusion, leading one to believe that the instrument should be able to continue detecting these peaks at 1kHz rates, as the peak shapes can clearly be seen in the 10 Hz full spectrum datasets.



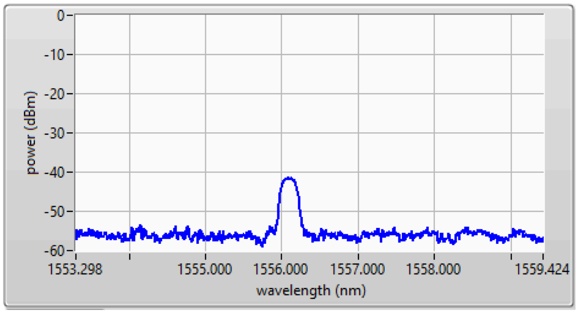


Figure 5. Averaged FS 16 FBG array with >28 dB insertion loss.

Figure 6. 1556 nm zoomed view of Figure 5 spectrum.

Given the apparent remaining SNR, it is tempting to think that the instrument should be able to detect these peaks at 1 kHz as well. However, it is key to recall that these spectral traces are the fruits of multiple averaged datasets, and that it is from a single 1kHz raw dataset (as yet unseen) that peak detected data is generated.

The images of figure 7 illustrate the differences in SNR between single acquisition 1kHz data and averaged full spectrum clearly. The top left trace shows the instantaneous single raw data trace from the FBG array with 28 dB loss. Note that unlike the averaged full spectrum trace, the FBG peaks are barely visible above the noise floor. When power calibrated (top right) the low SNR is even more apparent. In the bottom left trace, the amplitudes of the differentiated signals are both very small and unstable, falling well below the Threshold signal set as part of the peak detection algorithm (see TN1360 for algorithm setting details.)

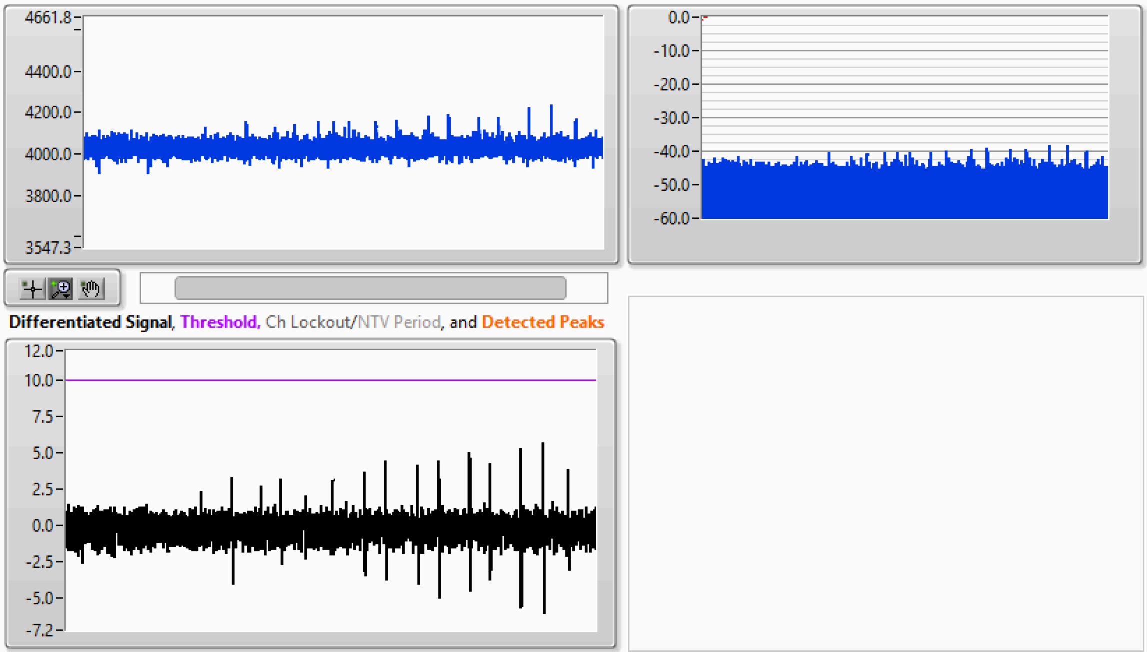


Figure 7. Single acquisition view of the same array with 28 dB dynamic range.

Figure 8 shows a 1556 nm zoom view of the same signals as those from Figure 7. From these images, it should be visibly apparent that on a single 1kHz acquisition at this level of system loss, the noise is every bit as strong as the signal. The Threshold setting value for the PD algorithm cannot be lowered significantly without risk of false peak detections coming from the noise floor. Clearly, loss of the sensors has exceeded the reach of the dynamic 1kHz data acquisition path and algorithm. It is only from internal spectral averaging/post-processing of non-real-time full spectrum data that the 10Hz spectral traces maintain additional SNR and dynamic range.

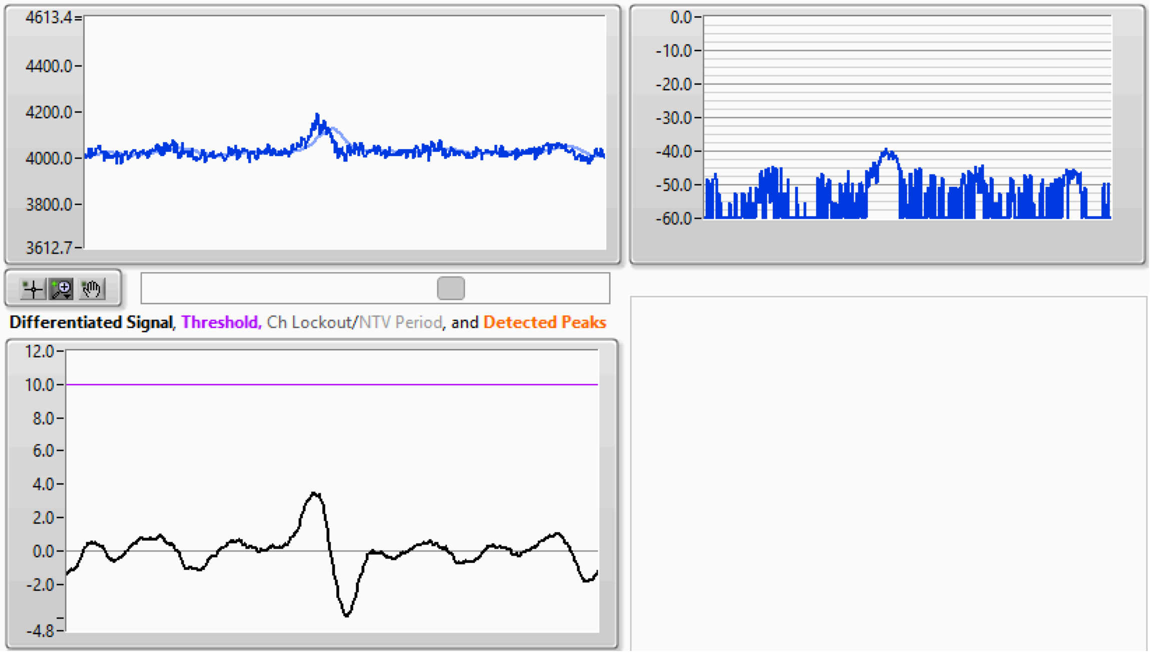


Figure 8. 1556 nm zoomed view of Figure 7 signals.

2.3. Changing speeds to enhance reach

There is, however, one significant method that can be employed to increase the instantaneous loss budget of the x55 Hyperion interrogator, and that is to reduce the actual scan rate of the laser.

When the laser scan rate is reduced, data acquisition at the ADC level continues at the same rate. However, rather than each acquired raw full spectrum data point being represented by a single ADC conversion, with reduce scan speed, each FS data point can be fed from multiple ADC conversions being first averaged inside of the FPGA itself. In other words, by slowing down the laser, the system can perform averaging on data BEFORE the real-time peak detection algorithms run, thereby actually increasing the reach of the peak detection algorithms and the loss budget (or peak detection) dynamic range of the system.

Consider the same 16 FBG array as seen in Figure 5, again with 28 dB of in-line insertion loss. However, this time, the sweep rate of the x55 Hyperion laser has been reduced to a rate of 100 Hz. Figure 9 shows the same array with approximately the same peak-to-floor SNR are the 1kHz acquired data from Figure 5.

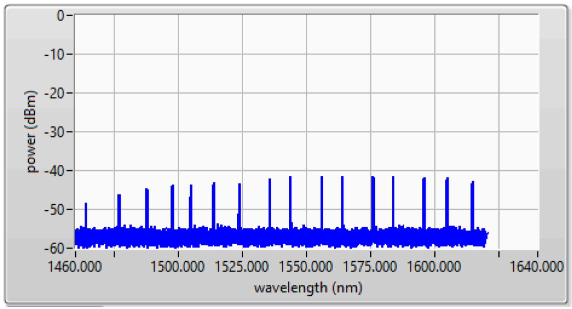


Figure 9. 28 dB loss array measured at 100 Hz.

From this view alone, any difference is not apparent.

However, note the differences in signal quality between two images 10(a) and 10(b) below. Figure 10(a) is a reproduction of the bottom left image of Figure 8 and represents the differentiated signal from a 1kHz acquisition. 10(b) represents the differentiated signal from a 100 Hz scan and carries the benefit of 10 ADC signal averages before being fed into the PD algorithm.

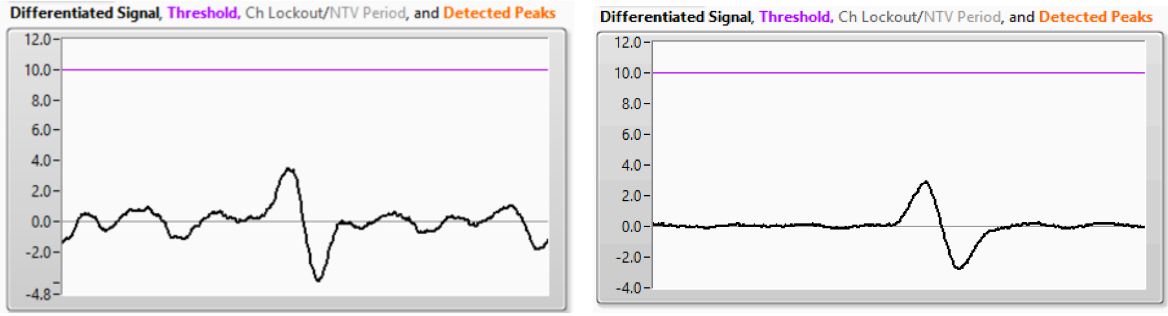


Figure 10. (a) 1kHz differentiated signal. (b) 100 Hz differentiated signal

Given the reduction in noise signal intensity, it is now safe to reduce the Threshold setting (as outlined in TN 1360) to detect the peaks and successfully overcome the 28 dB of system loss.

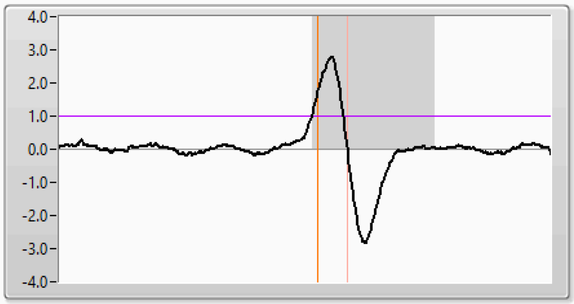


Figure 11. Modified threshold value afforded by ADC averaging noise reduction.

As a result of the change to 100 Hz scanning and an a correspondingly appropriate Threshold setting modification, the system is able to pick up 5 more dB of peak dynamic range and successfully measure the sensors with higher levels of loss.

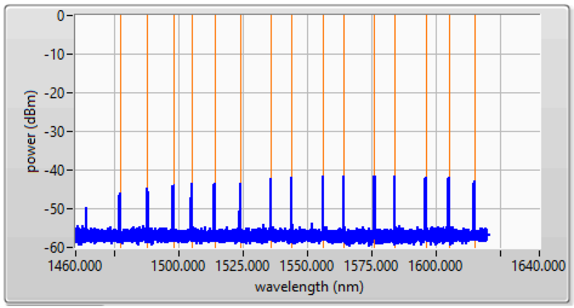


Figure 12. High loss sensor array successfully measured at 100 Hz.

In summary, there is quite a bit of full spectrum averaging and post processing that takes place in Hyperion firmware such that full spectrum traces represent the real optical spectrum of the sensors as accurately as possible. However, that post-processed data s not the source for the internal peak detection data at full 1kHz rates, and the full spectrum signals will always offer a deeper view than that PD algorithms will themselves follow. By reducing the scan rate of the laser and making a corresponding change to the PD Threshold setting, an additional 5 dB of peak dynamic range can be gleaned from the system at 100 Hz.