1. Introduction

This document will provide an overview of the manner in which Hyperion instruments derive wavelength from measured optical channels and some of the strengths/advantages of its optical architecture.

1.1. Covered topics

This documents will explain the nature and purpose of each optical reference channel in the Hyperion architecture, the manner in which data is computationally used to derive wavelength information, as well as additional operational benefits of this architecture is it relates to internal error detection.

1.2. Scope

The methods and attributes described in this document are applicable to all instruments within the x55 product family, including si155, si255 and si255 EV models.

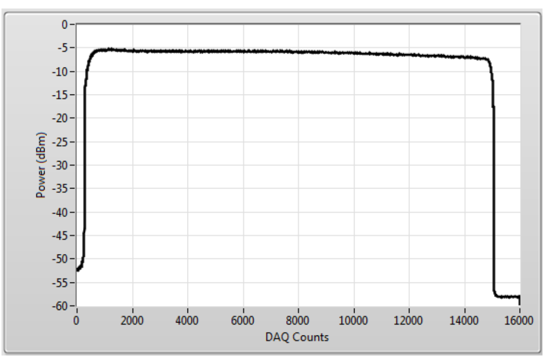
2. Overview of optical architecture

2.1. Receiver Architecture

From the swept wavelength source comes one of the major platform strengths: multiple receiver channels that provide the module complete self awareness about would-be failure modes.

2.1.1. Parallel Referencing Channel

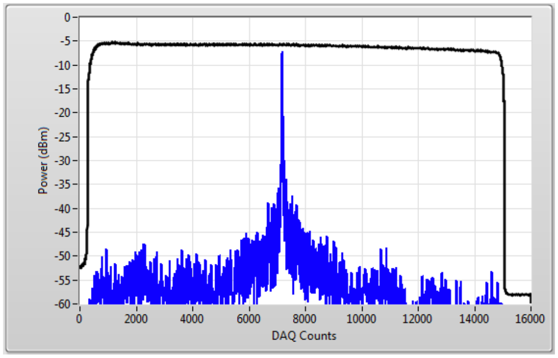
2.1.1.1. Power Reference Channel

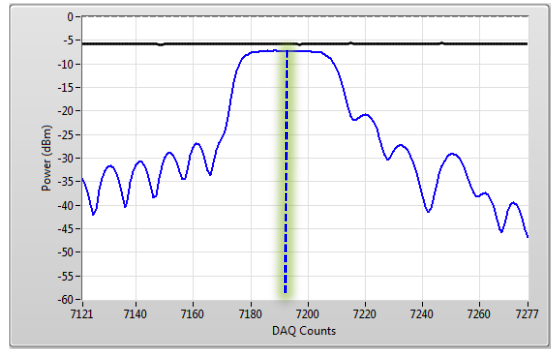


This traces is essentially comparable to that of a power meter vs time of optical source, showing actual power from swept spectrum optical source resolved during a single source sweep. This channel can be used to monitor the health of the optical source, as well as to provide continuous source shape normalization to other reference and DUT channels, assuring robust and high fidelity signal and fault detection algorithms: the focus can be on the measured reference and/or not and not obfuscated by small, time varying changes in source shape or intensity.

2.1.1.2. Reference FBG

First (simple, robust) indicator of wavelength in the system





Given a known nominal wavelength of the FBG (known very accurately with thermistor monitoring), an first association between time and wavelength is made. In this case, it is known that 1545nm is seen at a value of just below 1500 DAQ counts. Should that "peak" be seen at 2500 counts, the bias voltage for the swept spectrum light source control would need to be increased. Were that peak seen at 500 counts, the bias voltage for the swept spectrum light source control would need to be decreased. In this way, the FBG signal is the first element used in both wavelength calibration and closed loop source control.

Fail-safe: Without successful detection and control of the FBG signal, no additional processing steps need be made that could result in erroneous wavelength readings.

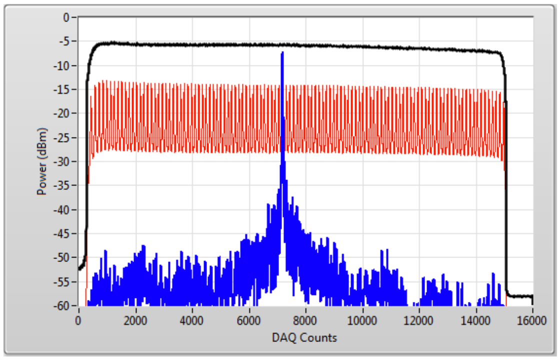
DAQ Counts	FBG Wavelength
7192	~ 1545.5

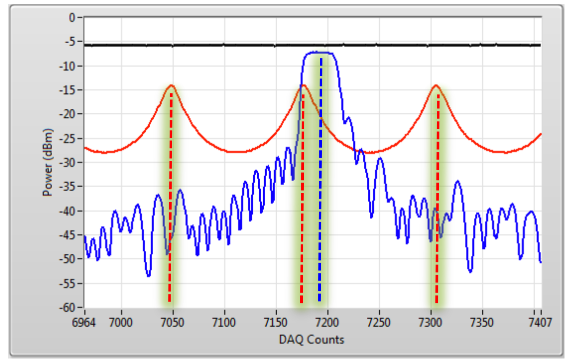
2.1.1.3. Reference AFPI

Having successfully centered (biased) the swept spectrum light source using the FBG signal, the AFPI signal can be used to control and calibrate the entirety of the source sweep and feed back swept source scan amplitude (how far to scan the swept spectrum light source).

An AFPI is an "infinite", linearly spaced, athermal wavelength reference of known frequencies. This Telcordia certified technology has been used for over a decade in countless deployments as telecom transmitter source wavelength lockers. By design, the AFPI peak spacing cannot be appreciably nonlinear. If you can see it, it has the correct, known spacing. Small shifts in the exact resonance modes are possible with temperature (2 -10 pm over 70 degrees C and will be ultimately validated by a fail-safe measurement of the internal NIST traceable gas cell.

The AFPI in this example happens to have an FSR (spacing) = 99.9861 GHz (~800pm) and a Ref Peak = 194.0872 THz (1544.626 nm)





With the AFPI, a simple lookup table between detected AFPI counts and known AFPI wavelengths is established. The thermally monitored FBG provides a unique marker with which to identify specific AFPI peaks in the otherwise "infinite" array of evenly spaced peaks.

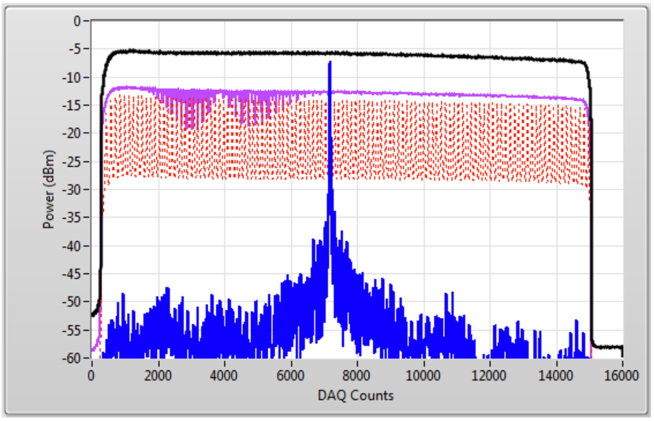
DAQ Counts	FBG/AFPI Wavelength
...	...
7048	1544.626
7177	1545.423
7192	~ 1545.500
7305	1546.219
...	...

At this point, the wavelength calibration is completely functional, able to convert timing signals from unknown DUT channels into calibrated wavelength. Before applying this functionality to critical sensor measurements, however, the calibration is first "tested" against an internal, NIST traceable, absolute wavelength standard.

2.1.1.4. NIST Traceable Acetylene Gas Cell

With the swept spectrum light source now in closed loop control, wavelength measurements are referenced to the athermal wavelength locker (AFPI device). Already, this basis for calibration far exceeds mechanical alignments of diode arrays or external cavity lasers, or swept aperture optical spectrum analyzers running in open loop, with regard to stability and continuous referencing. Hyperion goes on to then use one more channel for absolute wavelength and traceability.

Concurrent with the power reference, FBG, and AFPI traces, the Hyperion module continually take simultaneous scans of a $^{12}C_2H_2$ Acetylene Absorption Reference, shown below as the purple trace.

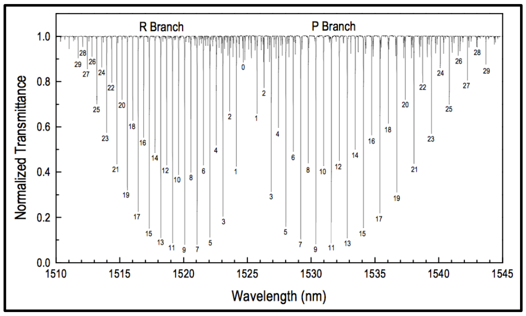


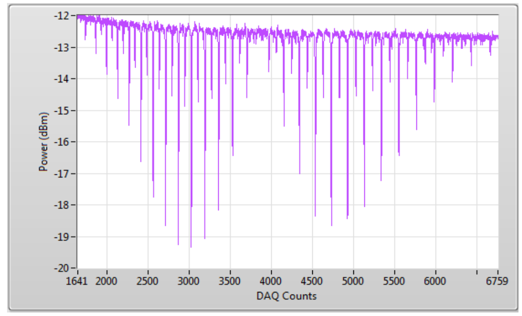
Because Acetylene is an internationally recognized primary wavelength standard with certified absolute wavelength values, comparison of the Hyperion's calibrated measurements can be made with published and recognized absolute values from:

NIST Special Publication 260-133 2001 Edition - *Standard Reference Materials*
Acetylene 12C2H2 Absorption Reference for 1510 nm to 1540 nm Wavelength Calibration—SRM 2517a

R Branch	Wavelength (nm)	P Branch	Wavelength (nm)
29	1511.7304(3)	1	1525.7599(6)
28	1512.0884(3)	2	1526.3140(3)
27	**1512.45273(12)**	**3**	**1526.87435(10)**
26	1512.8232(3)	**4**	**1527.44114(10)**
25	1513.2000(3)	**5**	**1528.01432(10)**
24	1513.5832(3)	**6**	**1528.59390(10)**
23	1513.9726(3)	7	1529.1799(3)
22	1514.3683(3)	8	1529.7723(3)
21	1514.7703(3)	9	1530.3711(3)
20	1515.1786(3)	**10**	**1530.97627(10)**
19	1515.5932(3)	11	1531.5879(3)
18	1516.0141(3)	12	1532.2060(3)
17	**1516.44130(11)**	**13**	**1532.83045(10)**
16	1516.8747(3)	**14**	**1533.46136(10)**
15	1517.3145(3)	15	1534.0987(3)
14	1517.7606(3)	16	1534.7425(3)
13	1518.2131(3)	17	1535.3928(3)
12	1518.6718(3)	18	1536.0495(6)
11	**1519.13686(11)**	19	1536.7126(3)
10	1519.6083(3)	20	1537.3822(3)
9	1520.0860(3)	21	1538.0583(3)
8	1520.5700(3)	22	1538.7409(3)
7	**1521.06040(10)**	**23**	**1539.42992(11)**
6	1521.5572(3)	**24**	**1540.12544(11)**
5	1522.0603(3)	**25**	**1540.82744(11)**
4	1522.5697(3)	26	1541.5359(3)
3	1523.0855(3)	27	1542.2508(3)
2	1523.6077(3)		
1	**1524.13609(10)**		

By comparing how the Hyperion module measures the absorption lines in comparison to the NIST standard, we are able to quantify and compensate for any offsets in the system, be they electrical, optical, thermal, mechanical, or otherwise.

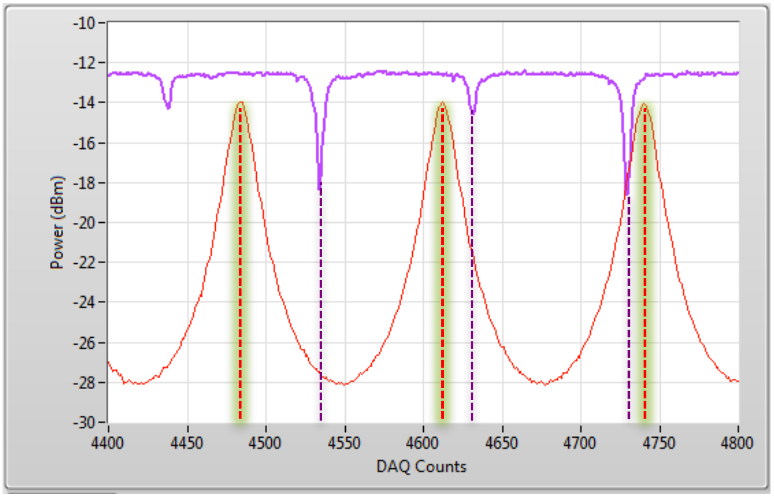




Above, the plot to the left shows the spectrum as characterized by NIST and associated absorption line labels that correspond to the published values in the table. It is important to note that the amplitude or depth of these lines have no physical bearing on the wavelength accuracy. Operating temperature and pressure do not materially influence the wavelength centers of absorption. The specific wavelengths absorbed by the gas are immutable molecular properties that can be used to both certify and further correct any and all measurements made by the Hyperion interrogator.

The purple trace above shows the same spectrum as detected by the Hyperion interrogator in the time domain. The next section goes on to show how this trace is wavelength calibrated by the AFPI the result is compared to the traceable NIST-certified molecular absorption lines.

Zooming in on the simultaneously detected AFPI and gas cell traces shows the peak detection of the "known" AFPI trace (red) and null detection of the "unknown" Acetylene peaks



Using the now-known relationship between counts and wavelength that has been derived from the AFPI channel, simple linear interpolations are made to convert the detected counts of the gas cell into "measured" wavelengths, which can then be compared to NIST published values.

DAQ Counts	AFPI Wavelength	GC Counts	GC "measured"	GC Actual	Correction (nm)
…	…				
4484	1528.874				
		4534	1529.1787**	line P7 – 1529.1799	-0.0012 ***
4612	1529.654				
		4631	1529.7699	line P8 – 1529.7723	-0.0024
		4729.5	1530.3709	line P9 – 1530.3711	-0.0002
4740	1530.435				
…	…				

Treat Gas cell as we would and DUT and interpolate from know references to find GC absorption line values:

** GC "measured" = 1528.874 = ((4534 – 4484)/(4612 – 4484))*(1529.654 – 1528.874) = 1529.1787

Then compare "measured" gas cell value against published NIST standard to find wavelength correction value:

*** 1529.1787 – 1529.1799 = -0.0012

All of the available gas cell absorption lines are analyzed in this manner on each scan, resulting in an average offset, which is used to correct for any thermal drifts in the AFPI reference. In this example, the average offset of -0.0012 nm would be applied to the measurements of any DUT sensors.

By calibrating the full wavelength range of the source on each scan and comparing to a NIST-traceable primary wavelength standard, the Hyperion module can generate a host of self-diagnostic information that can be used to mitigate risk during operation. The next section will build upon this understanding to demonstrate how Hyperion self reporting can be used to identify, predict, and prevent potential failure modes of the module.

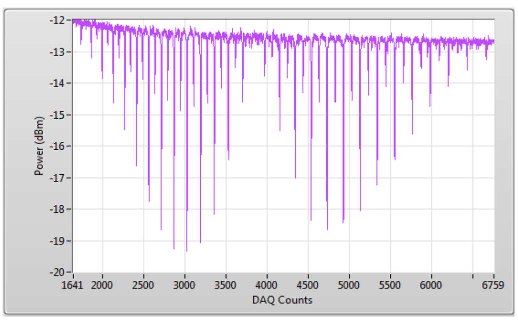
3. The Gas Cell as Gatekeeper. No Bad Data Shall Pass.

3.1. The Two Man Rule.

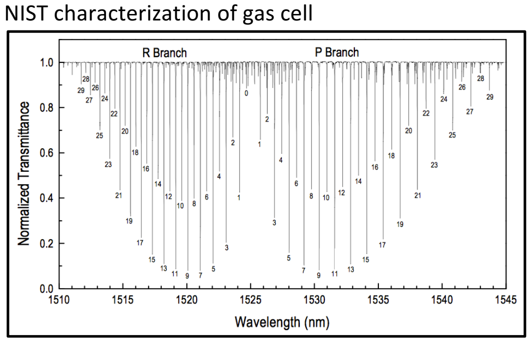
*"The **two-man rule** is a control mechanism designed to achieve a high level of security for especially critical material or operations. Under this rule all access and actions requires the presence of two authorized people at all times."*


Together, the swept wavelength light source, the FBG, and the AFPI calibration system are "one man" for evaluating the spectral absorption lines of the gas cell. NIST and their published gas cell standard are the "second man". No critical operations will be performed until both the Hyperion module and the NIST data they are both in agreement. This "two man" rule will be observed on every scan of the Hyperion interrogator during its lifetime.

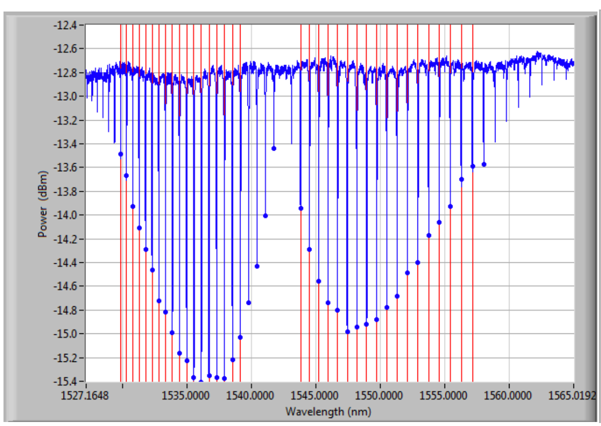
Hyperion characterization of gas cell



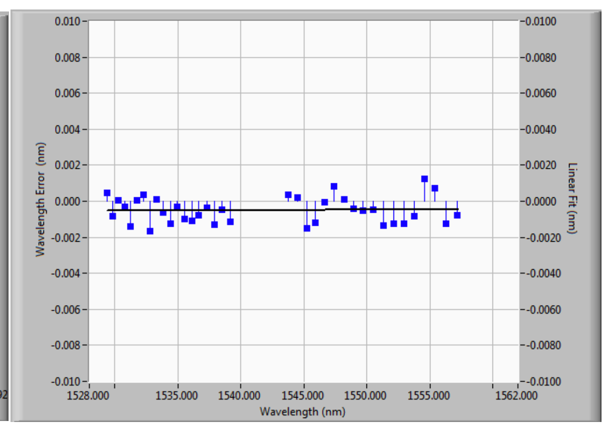
NIST characterization of gas cell



Hyperion Data (blue) compared to NIST data (red)



Quantitative differences showing agreement between both "men".



Interrogator is validated and both functional and accurate. Data is delivered to the user.

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3.2. Failure mode mitigation by Gas Cell "Key Fit"

The gas cell can also be considered as specifically keyed "lock", guarding a door through which not data shall pass unless the correct key is used.

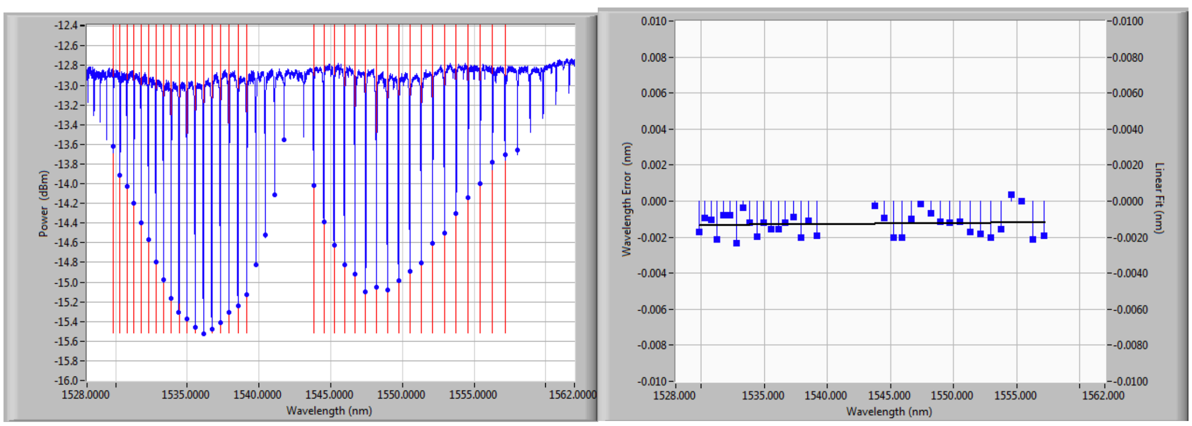
Gas cell spacing is non-uniform, both in wavelength and frequency. Correctly measuring the gas cell spectrum and comparing it to published spectra can serves as the "lock and key" mechanism without which no wavelength data shall be served or robot movements made/continued. The vast majority of conceivable errors in FBG, AFPI, electrical drive, calibration, or FPGA code distribution can be trapped before any wavelengths are transmitted to the user based upon this gas cell spectrum lock and key, implemented as a hard go/no go procedure in the ISI FPGA.

For these illustrations, all faults have been induced on a test EUT, gas cell spectra have been captured and compared to NIST published absorption lines for "key fit" evaluation.

3.3. Fabry-Perot Drift

The following potential failure modes have been reference from the ISI-generated MOI FMEA summary, shared on 2014.09.11

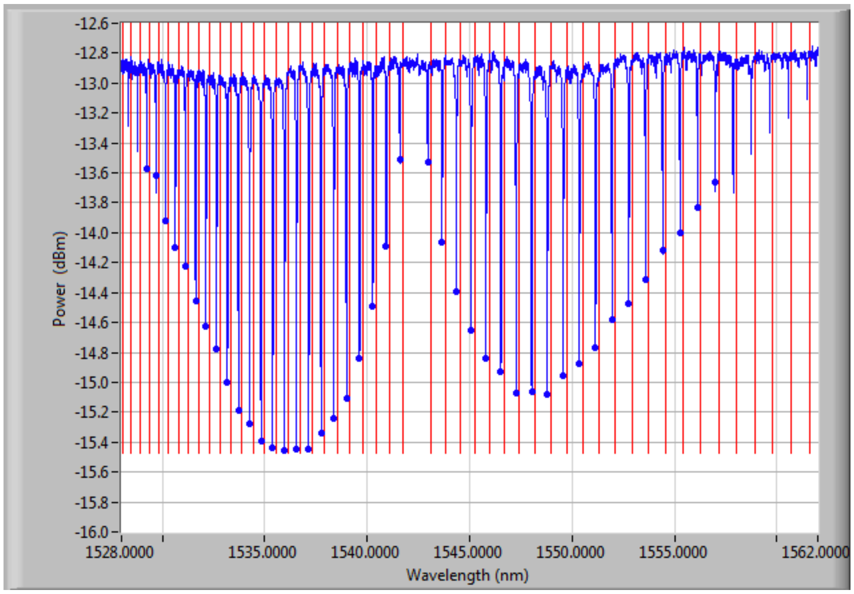
3.3.1. Minor Fabry Perot Drift (1 pm)



The key fits, and the AFPI is corrected within its operational limits. Data is corrected for small drifts.

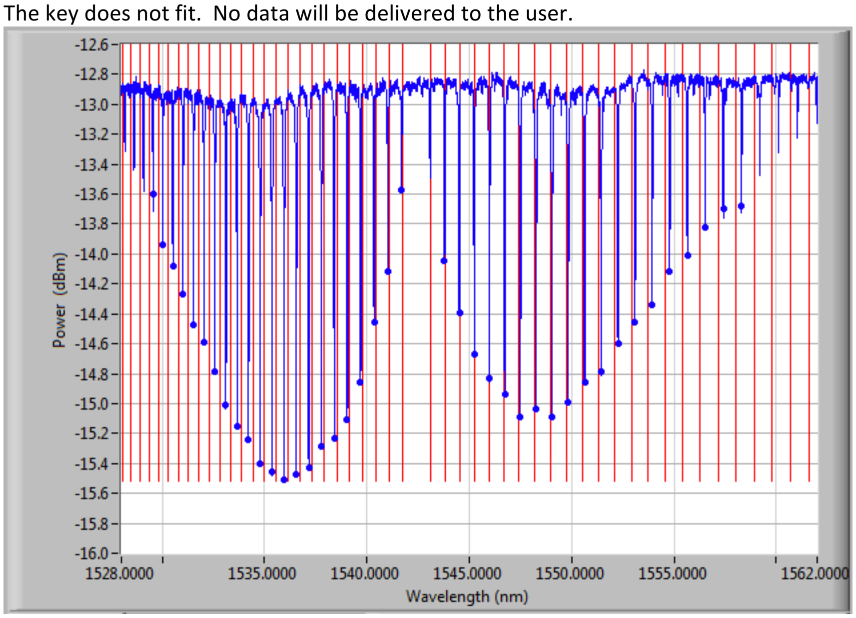
3.3.2. Major Fabry-Perot Drift (200 pm)

The optical spectrum is uniformly offset from the truth.
The key does not fit. No data will be delivered to the user, no force feedback applied.



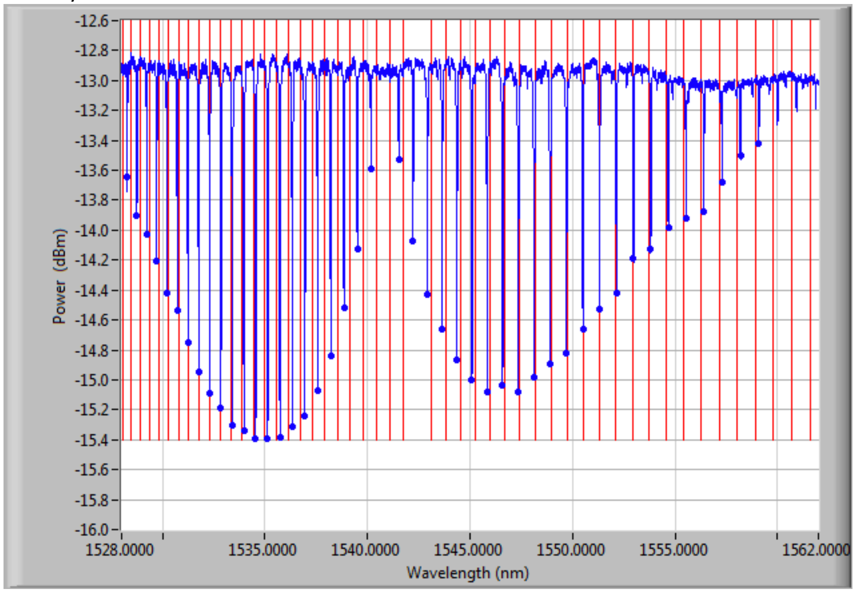
3.4. AFPI FSR error

The optical spectrum has a non-uniform wavelength deviation from the truth over wavelength.
The key does not fit. No data will be delivered to the user.



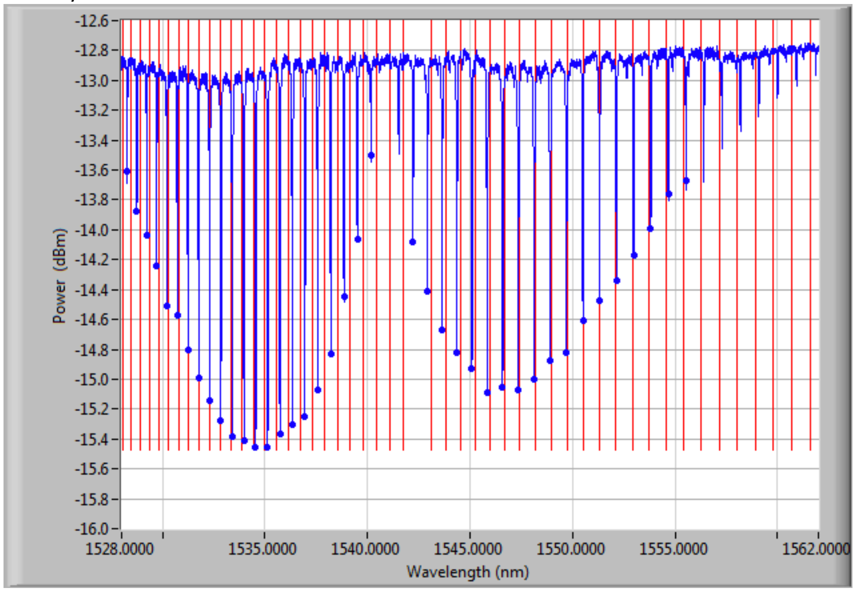
3.5. FBG measurement error

The optical spectrum is uniformly offset from the truth.
The key does not fit. No data will be delivered to the user.



3.6. Thermistor Measurement Error

The optical spectrum is uniformly offset from the truth.
The key does not fit. No data will be delivered to the user.



4. Hyperion Error Detection Capabilities - Failure Prediction and/or Diagnostics

4.1. Power failures

4.1.1. Power supply interruption

Presently monitored by appropriate current/voltage monitors direct to FPGA

4.1.2. Power conversions (DC/DCs)

Presently monitored by internal electrical circuitry.

4.2. Light Generation (Swept Spectrum Source) Failures

4.2.1. Source electronic supply/control failures

4.2.1.1. Pump diode over/under current

onboard current monitors connected to FPGA

4.2.1.2. TEC over/under current

onboard current monitors, connected to FPGA

4.2.1.3. TEC over/under temp

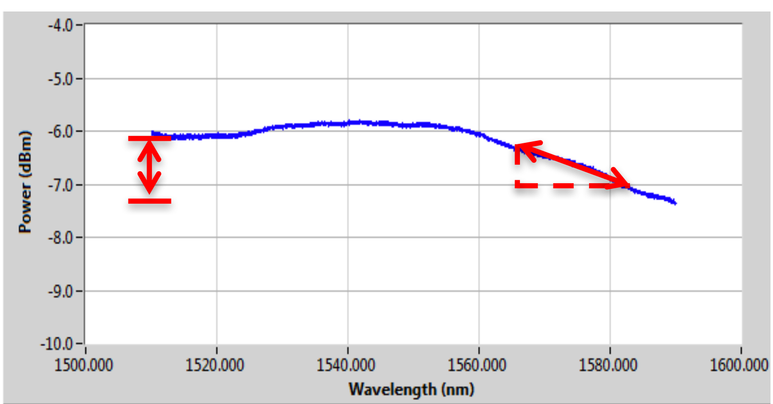
onboard temperature monitors, connected to FPGA

4.2.1.4. Swept spectrum light source control parameter (bias and scan amp) checks/limits

4.2.2. Source Optical Failures

parallel wavelength calibrated power reference channel serves as a constant monitor of optical power, range, and shape of source…a unique capability of Hyperion and a feature that cannot be matched by diode array technology (without a second diode array…)

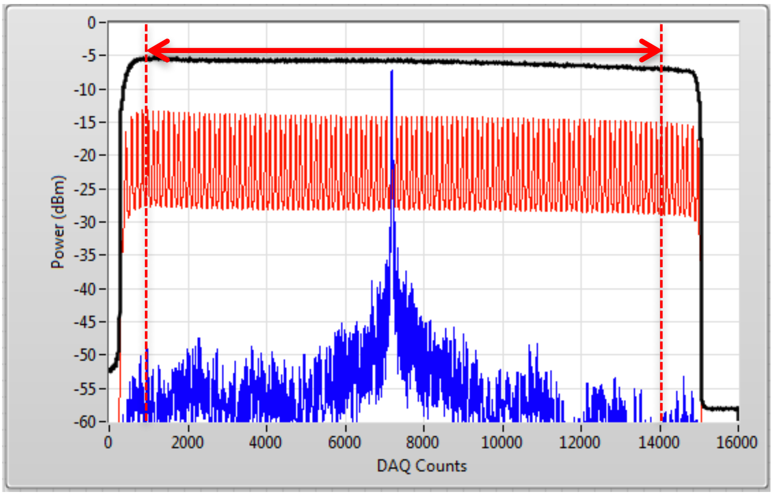
4.2.2.1. Light source total and wavelength dependent power variations



metrics will be implemented in FW to report on any degree of change in source characteristics as they may be a predictor of application failure, be they total power, max-min flatness values, or spectral rates of change.

4.2.2.2. Light source wavelength range variations

Self aware in both count space and calibrated wavelength space



checks will be implemented for light source total range and out of band “safety margin”

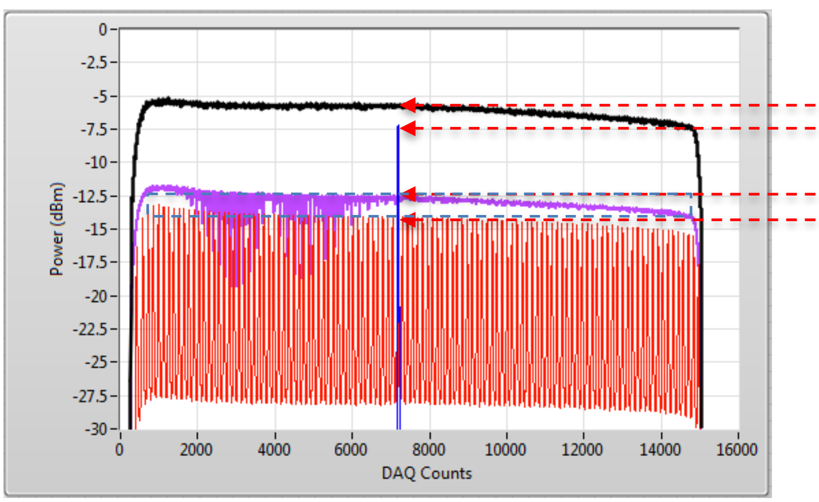
4.2.3. Receiver/Calibration Optics Failures

4.2.3.1. Reference FBG thermal monitor check against board temp

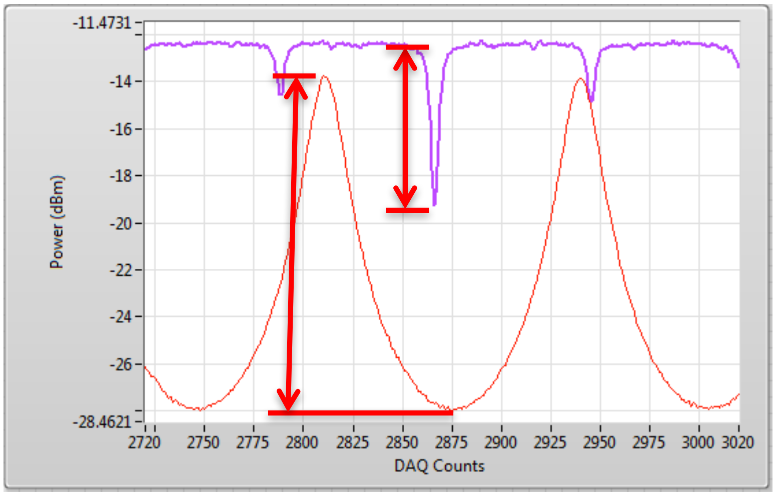
confirm correct starting point calibration

4.2.3.2. Relative power level checks to confirm optical coupling ratios to design

checking average power levels and individual flatness levels ensure that optical circuits are working as designed



4.2.3.3. Optical reference channel flatness, contrast, and power levels

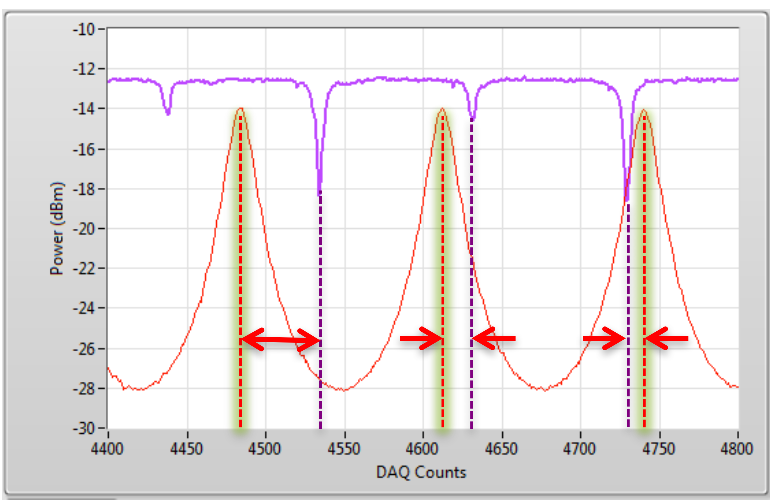


health checks for optical reference components based on expected parameters. proper contrast ensures gas cell pressures and AFPI coupling alignments.

4.2.3.4. AFPI/Acetylene cell agreement

While the gas cell can be used to correct for small thermal or aging effects of the AFPI, it can also be used to identify components operating outside of the normal expected ranges and prevent potential catastrophic failures.

Offsets between gas cell and AFPI lines are expected to be stable within 10 pm over the lifetime of the module. Any deviations beyond that point imply an unacceptably unstable AFPI reference that should be taken out of operation.



NOTE: such a catastrophic AFPI failure has never been recorded in a field module, but remains a theoretical concern that parallel processing of a gas cell can predict.