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# Technical Note 1447 | HYPERION CALIBRATION AND TRACEABILITY

**Micron Optics Inc.**
**1852 Century Place NE**
**Atlanta, GA 30345 USA**

**phone 404 325 0005**
**fax 404 325 4082**
**www.micronoptics.com**

Table of Contents


1. INTRODUCTION ..... 3
   - 1.1. Calibrated Parameters ..... 3
   - 1.2. Scope ..... 3
2. LEVELS OF STANDARDSA AND TRACEABILITY CHART ..... 3
3. TRACEABILITY THROUGH DOCUMENTATION ..... 5
   - 3.1. Field/Remote Certifications and/or Production standards (iii and iv) ..... 5
   - 3.2. Inter-Laboratory Primary Standards (ii) ..... 7
   - 3.3. National Standards Laboratory (i) ..... 7
4. HYPERION INTERROGATOR SPECIFICATION DEFINITIONS AND TEST METHODOLOGY ..... 8
   - 4.1.1. Wavelength Accuracy ..... 8
   - 4.1.2. Repeatability ..... 8
   - 4.1.3. Stability ..... 9
   - 4.1.4. Resolution ..... 10
   - 4.1.5. Reproducibility ..... 10

## 1. Introduction

This document will provide an overview of the manner in which Hyperion instruments are calibrated, the the types of components and instruments that are used for that calibration, and the path to traceability for each of the measured parameters.

### 1.1. Calibrated Parameters

As a family of optical sensor interrogation products, the HYPERION series of interrogators are primarily concerned with making accurate and repeatable measurements of optical wavelength. As such, most of the content of this technical note will center around the characterization and quantification of optical wavelength measurements. Although not a primary measure of the instrumentation, optical power and/or loss are often instrumenting in setting up a stable optical sensors measurement. As such, calibration and traceability of these parameters is also briefly addressed.

### 1.2. Scope

These principles and methods described in this document are applicable to all instruments within the x55 product family, including si155, si255 and si255 EV models. In basic principles, these methods also apply to historical x25 and optical interrogator products as well.

## 2. Levels of standardsa and traceability chart

The principles of traceability to nationally or internationally recognized standards require the following elements:

1. a continuous series of comparisons from the desired functional measurement all the way back to recognized standards
2. corresponding calculations of aggregate measurements uncertainties accompanied by each of those comparisons
3. a documentation path to certify each of those comparisons and associated uncertainties
4. evidence that valid methods were respected at each chain of measurement by competent parties, referencing SI units were available
5. definition and respect for calibrating timing intervals for each measurements link on the calibration chain.

In the case of the Hyperion interrogators, the chain of calibration for wavelength, power, and attenuation are respected as is shown in the following chart:

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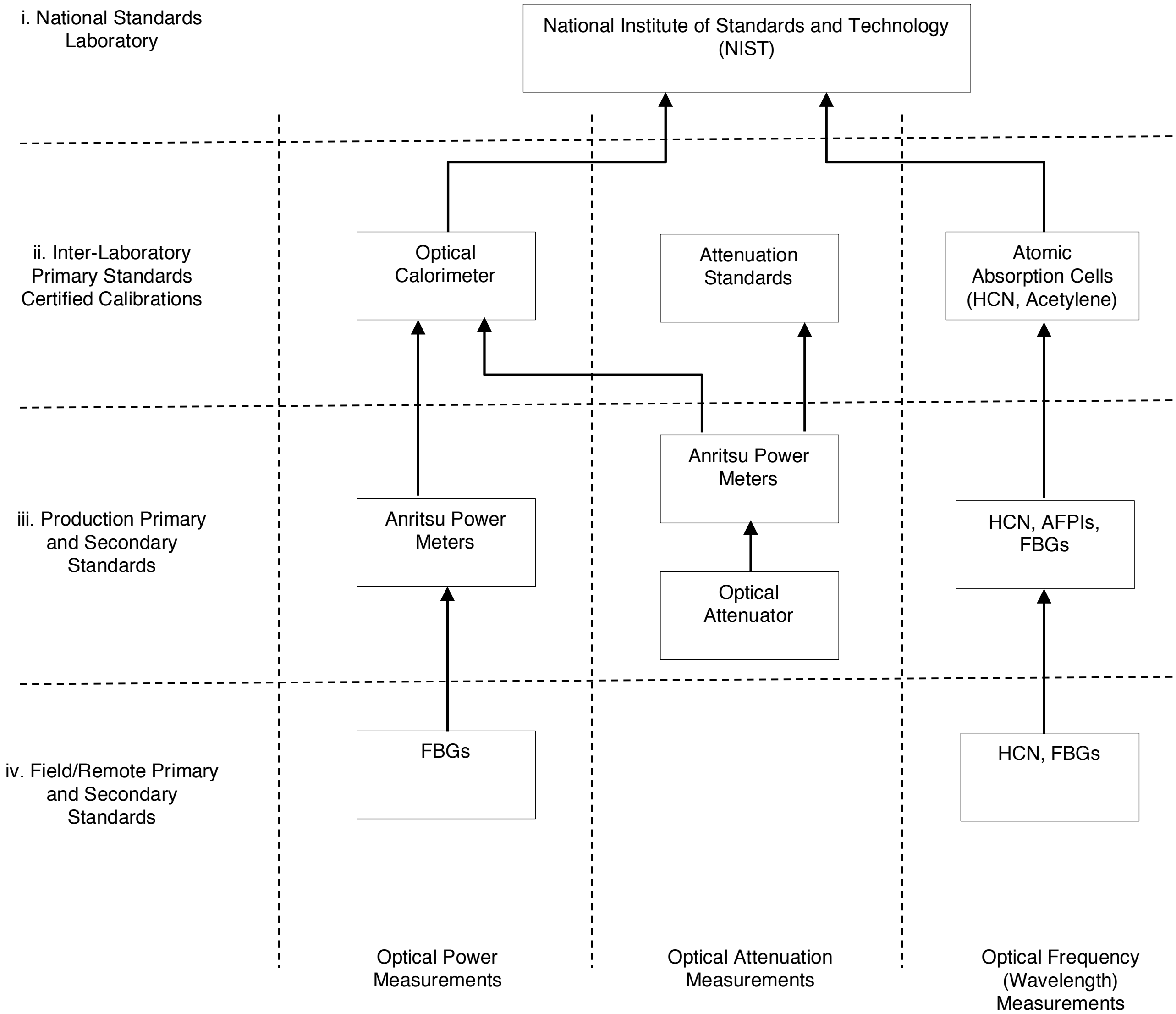


In the specific case for wavelength measurements of a Hyperion interrogator, these levels are represented as follows:

i. National Standards Laboratory: SRM2519 and the pressure shift addendum.
   This is how we know for sure that HCN is "right".
ii. Inter-Laboratory Primary Standards: Vendor supplied HCN cell and reference (commercial implementation of item I).
   Calculated uncertainty and offset from pressure provided by the vendors
iii. Production Primary and Secondary Standards: expansion of HCN accuracy across broader wavelength range and over alternate spectral shapes, as to be applied to Hyperion instrument. Accuracy "conferred" to AFPI and/or FBG as makes sense for use
iv. Field/Remote Primary and Secondary Standards: calibrated directly to both primary and secondary reference artifacts.

## 3. Traceability through documentation

In the case of the Hyperion Optical Sensing Interrogators, traceability of measurement is affirmed through the following steps (shown in reverse order relative to the chart of the pervious section:

### 3.1. Field/Remote Certifications and/or Production standards (iii and iv)

Here, calibration of the interrogator is performed by comparison to a certified Hyperion Calibration artifact, which is comprised of both Primary and Secondary wavelength standards. Evidence of this calibration and a traceability path to the Primary and Secondary production standards is shown in the Instrument Certification of Calibration, as shown below.

**Micron Optics, Inc. Certificate of Calibration** | Hyperion Sensor Interrogator

# Certificate of Calibration

Certificate No.: 664-74720-9292-012

| | | | |
|---|---|---|---|
| **Manufacturer :** | Micron Optics, Inc. | **Description :** | Hyperion Sensor Interrogator |
| **Model No. :** | si255-04-ST/160-NO | **Serial No. :** | HIA123 |
| **Calibration Number :** | HIA123_3280066344.4354719 | **Date Calibrated :** | 2016.02.21 |

This certificate certifies that the reference artifacts identified above have been successfully calibrated to the traceable reference standards, also listed below. This document also serves to state that the calibration was processed under Micron Optics' Quality Management System procedures, which are in compliance with the requirements of IOS9001. Documents related to the manufacture, testing, calibration, and final inspection of this product are kept on file at Micron Optics.

**As Received Condition**
New

**As Shipped Condition**
This product meets published specifications.

**External Reference Components and Test Equipment**

**Hyperion Calibration Artifact**
Manufacturer: Micron Optics
Model: Hyperion Calibration Artifact
Serial Number: CAAAPV
Date of Calibration: 2015.11.18

Comprised of:

**Primary Traceable Wavelength Reference Type**

Hydrogen Cyanide $H_{13}CN$, manufactured by Wavelength References, Inc.
Equivalent of the NIST SRM 2519, wavelength calibration reference for 1530nm – 1560 nm
http://www.boulder.nist.gov/div815/SRMS/Certificates/2519Acer.pdf

**Specific Wavelength Traceable Artifact**

Reference Hyperion Reference Artifact Certificate of Calibration

**Secondary Wavelength Artifacts (one or more may be included)**

**Athermal Fabry-Perot Interferometer (AFPI), Reference Fiber Bragg Gratings (FBGs)**

Reference Hyperion Reference Artifact Certificate of Calibration

**Secondary Power Refernce Instrument**
Manufacturer: Anritsu
Model: XXX-XXX-1234
Serial Number: ABCD1234
Date of Calibration: 2015.11.18

Micron Optics, Inc. | 1852 Century Pl, Atlanta, GA, 30345 | 404.325.0005 | info@micronoptics.com

The Field/Production calibration artifacts are then themselves shown through a Certificate of Calibration to be traceable to (first) Inter-Laboratory Primary Standards with all associated calculations of uncertaintly, as follows:



# Certificate of Calibration

Certificate No.: 664-74720-8913-003

| | | | |
|---|---|---|---|
| **Manufacturer :** | Micron Optics, Inc. | **Description :** | Optical Calibration Reference |
| **Model No. :** | Hyperion Calibration Artifact | **Serial No. :** | CAAAPV |
| **Calibration Number:** | CAAAPV_3391177455.465820 | **Date Calibrated :** | 2015.11.18 |

This certificate certifies that the reference artifacts identified above have been successfully calibrated to the traceable reference standards, also listed below. This document also serves to state that the calibration was processed under Micron Optics' Quality Management System procedures, which are in compliance with the requirements of IOS9001. Documents related to the manufacture, testing, calibration, and final inspection of this product are kept on file at Micron Optics.

**Internal Reference Components**

**Primary Traceable Wavelength Reference Type**

Hydrogen Cyanide $H_{13}CN$, manufactured by Wavelength References, Inc.
Equivalent of the NIST SRM 2519, wavelength calibration reference for 1530nm – 1560 nm
http://www.boulder.nist.gov/div815/SRMS/Certificates/2519Acer.pdf

**Specific Wavelength Traceable Artifact**

Manufacturer: Wavelength References
Model: HCN-13-H(65)-100-FCAPC
Serial Number: 0150010
Date of Manufacture: 2015.03.03

**Secondary Wavelength Artifacts (one or more may be included)**

Manufacturer: Micron Optics
Model: 100 GHz Athermal Fabry-Perot Interferometer
Serial Number:
Date of Manufacture:

Manufacturer: Technica SA
Model: 16 FBG Array, 1465 nm – 1615 nm
Serial Number: 530609262
Date of Manufacture: 2015.06.19

**Other Calibration Devices and Test Equipment Applied**

MOI sm125 Optical Sensing Interrogator
Serial Number: SIA9FY
Calibration Date: 2015.11.16

Itself containing an internal NIST traceable wavelength reference eference
Acetylene 12C2H2, manufactured by Wavelength References, Inc.
Equivalent of the NIST SRM 2517 and 2517A Wavelength calibration reference for 1510nm – 1540nm. http://www.boulder.nist.gove/div815/SRMS/Certificates/2519Acer.pdf

## 3.2. Inter-Laboratory Primary Standards (ii)

Having established a path for both interrogator can calibration artifact to Inter-Laboratory standards, it is then necessary to establish traceability from that standard back to an a nationally or internationally recognized standards. In the case of the HCN reference cells, this assurance comes in two forms from the vendor. The first of which is a production Certificate of Compliance that the correct gas cell species was used in the production of the cell and that the measured pressure of that cell ensures absorption behavior according to certified characteristics defined by the national laboratory (NIST in this case).

Manufacturer certifies gas species and pressure

Wavelength REFERENCES

*Certificate of Compliance*

Model: HCN-13-H(16.5)-100-FCAPC
Date: March 3, 2015
Serial Number: 0150010

Note: The cells absorption lines are referenced to fundamental molecular constants and as such are not subject to drift and errors that might be associated with other equipment and can be considered traceable to a physical constant. The user should reference measurements on similar cells from National Institute of Standards and Technology (NIST) or the High Resolution Transmission Molecular Absorption Database (HITRAN) for absorption wavelength values and error analysis. These units will not normally require a calibration cycle.

Test Temperature: 21°C

**Test Equipment:**
Agilent tunable laser 81640A
dBMoptics CSA2004

| Specification | Limits | Measured | Pass/Fail |
|---|---|---|---|
| Insertion loss | <3.0dB | 1.2dB | Pass |
| Gas Absorption spectra | Compare to HITRAN | | Pass |
| Absorption at 1536.7nm | | 3.2dB | Pass |
| Line Width | | 73.5 pm | Pass |
| Residual Artifacts | <0.1 dB | <0.01 dB | Pass |

**Note: 50 pm linewidth suggests 75 Torr pressure within the cell. This reduction in pressure amounts to a pressure shift of -0.02pm on the R9 line: 1536.11688nm to 1536.11686n. Original purchase date 1/10/2011.*

At the time of shipment this instrument met its published operating specifications. The information contained in this report is true and correct to the best of my knowledge. Please contact *Wavelength References* with any questions regarding this report.

Amy Davis-Bruner

Manufacturer certifies traceability to NIST

Wavelength λ References, Inc.

33874 SE Eastgate Circle, Corvallis, OR 97333- USA
Telephone: (541)-738-0528
Facsimile: (541) 738-0988(fax)
www.wavelengthreferences.com

**NIST Traceability for gas cells**

The question of NIST traceability of gas cell lines is a difficult one to answer due to the fact that the lines are based on fundamental energy levels of molecules. The specified accuracy of the gas cell lines also generally exceeds the accuracy of the measurement equipment. It is a fact that all acetylene molecules (of the same isotopes) are identical so, in the same environment, all acetylene lines are identical. The principle variation in gas cell environment is due to chemical purity and pressure.

At wavelength references all gas cells are measured for line depth and width with the results compared to results from an in house SRM purchased from NIST as well as published data both from NIST and HITRAN.

We purchase raw gas with a purity assay to assure purity of the raw material. The depth of a gas cell line for a particular gas cell length gives an independent measure of contamination when compared to published results.

Pressure gauges are periodically calibrated but the measured width of the gas cell line gives an independent measure of the gas cell pressure. NIST has performed a detailed error analysis of gas cell lines for their SRMs. By far the dominant source of error is due pressure uncertainty. The data on the NIST SRM2517A acetylene gas cell assumes a pressure of 50Torr ±10Torr or ±20%. When we analyze results from production over a long term at Wavelength References we see that we generally hold the pressure uncertainty to <±5%.

For long term stability our gas cell tubes utilize a melted glass seal. The leak rate from this type of seal is extremely slow, essentially zero for this use. This seal is also extremely robust to temperature and humidity unlike, for example, an epoxy seal.

By all these means we can say with assurance that Wavelength References gas cells are NIST traceable.

## 3.3. National Standards Laboratory (i)

Lastly, the theory of operation and assurance of absolute accuracy of the standard reference material (SRM) can be confirmed through reading the primary certification documents from NIST, addressing all fundamental uncertainties of the measurements (including pressure, for which the Inter-office standards are certified and carry additional uncertainty) and defending the "indefinite" nature of calibration assurance from HCN as a primary reference material (SRM).

NIST certifies gas species as primary SRM

**NIST Special Publication 260-137**
**2005 Edition**

*Standard Reference Materials®*

**Hydrogen Cyanide $H^{13}C^{14}N$ Absorption Reference for 1530 nm to 1565 nm Wavelength Calibration – SRM 2519a**

Sarah L. Gilbert
William C. Swann
Chih-Ming Wang

NIST characterizes pressure uncertainty

**Table 1. Line Center, Pressure Shift, and Pressure-Broadening Results for $H^{13}C^{14}N^{a}$**

| Line | Line Center Extrapolated to Zero Pressure (vacuum wavelength, nm) | Shift Coefficient | | Broadening Coefficient | |
|---|---|---|---|---|---|
| | | (pm/kPa) | (MHz/Torr) | (pm/kPa) | (MHz/Torr) |
| *R*23 | 1528.926232(10) | 0.060(2) | −1.02(3) | 1.0(3) | 17(5) |
| *R*21 | 1529.836643(10) | 0.071(2) | −1.21(3) | 1.4(3) | 24(5) |
| *R*18 | 1531.275090(10) | 0.085(2) | −1.45(3) | 2.2(3) | 38(4) |
| *R*15 | 1532.801111(10) | 0.085(2) | −1.44(3) | 3.2(2) | 55(4) |
| *R*12 | 1534.414943(10) | 0.058(2) | −0.98(3) | 4.3(2) | 73(3) |
| *R*10 | 1535.539723(10) | 0.026(2) | −0.45(3) | 4.9(2) | 83(3) |
| *R*9 | 1536.116809(10) | 0.005(1) | −0.09(2) | 5.0(2) | 85(3) |
| *R*8 | 1536.703707(22) | −0.021(6) | 0.35(9) | 5.1(1) | 87(2) |
| *R*7 | 1537.300409(27) | −0.034(7) | 0.58(12) | 5.1(1) | 86(2) |
| *R*5 | 1538.523322(11) | −0.083(2) | 1.39(3) | 4.8(2) | 81(3) |
| *R*3 | 1539.785605(12) | −0.111(2) | 1.87(4) | 4.0(2) | 67(3) |
| *R*1 | 1541.087342(10) | −0.092(2) | 1.55(3) | 3.0(2) | 50(3) |
| *R*0 | 1541.753026(11) | −0.066(2) | 1.12(3) | 2.6(2) | 44(4) |
| *P*1 | 1543.114083(10) | 0.043(2) | −0.72(3) | 2.6(3) | 44(4) |
| *P*4 | 1545.230028(10) | 0.091(2) | −1.52(3) | 4.0(2) | 68(3) |
| *P*5 | 1545.955208(10) | 0.084(2) | −1.40(3) | 4.5(1) | 76(2) |
| *P*9 | 1548.955546(11) | 0.001(2) | −0.02(3) | 5.4(1) | 90(2) |
| *P*10 | 1549.730587(10) | −0.024(1) | 0.40(2) | 5.3(1) | 89(2) |
| *P*11 | 1550.515630(11) | −0.050(2) | 0.82(3) | 5.2(1) | 86(2) |
| *P*14 | 1552.930882(14) | −0.112(3) | 1.86(4) | 4.3(2) | 71(3) |
| *P*16 | 1554.591255(16) | −0.139(3) | 2.30(6) | 3.5(2) | 59(3) |
| *P*17 | 1555.436539(12) | −0.146(2) | 2.41(3) | 3.2(2) | 52(3) |
| *P*20 | 1558.032905(22) | −0.151(5) | 2.49(9) | 2.2(3) | 36(5) |
| *P*23 | 1560.720279(11) | −0.134(2) | 2.19(3) | 1.4(3) | 23(4) |
| *P*24 | 1561.636345(10) | −0.126(2) | 2.06(3) | 1.2(2) | 19(4) |

[a] Results are for the measured lines of the $2\nu_3$ band of hydrogen cyanide $H^{13}C^{14}N$ at a temperature of 22°±2 °C. The line center vacuum wavelength results are for low-pressure conditions; our measurements (column 2) are values obtained by extrapolating the line center to zero pressure. The broadening coefficient is the pressure dependence of the FWHM of the Lorentzian component of the Voigt line profile. The uncertainties in the final digits of the values are indicated in parentheses. The uncertainties quoted are the expanded uncertainties obtained by applying a coverage factor $k=2$ (i.e., our quoted uncertainty is $\pm 2\sigma$).

NIST certifies calibration as "indefinite"

National Institute of Standards & Technology

**Certificate of Analysis**

Standard Reference Material® 2519a

High Resolution Wavelength Calibration Reference for 1530 nm – 1565 nm
Hydrogen Cyanide $H^{13}C^{14}N$

Serial No.:

This Standard Reference Material (SRM) is intended for wavelength calibration in the spectral region from 1530 nm to 1565 nm; the center wavelengths of 54 lines of the $2\nu_3$ rotational-vibrational band of hydrogen cyanide $H^{13}C^{14}N$ are certified. This SRM can be used for calibrating a variety of wavelength-measuring instruments such as optical spectrum analyzers, tunable lasers, and wavelength meters. SRM 2519a is a single-mode optical-fiber-coupled absorption cell containing hydrogen cyanide $H^{13}C^{14}N$ gas at a pressure of 3.3 kPa (25 Torr). The absorption path length is 15 cm and the absorption lines are about 15 pm wide. The cell is packaged in a small instrument box (approximately 32 cm long x 12.5 cm wide x 9 cm high) with two FC/APC fiber connectors for the input and output of a user-supplied light source. The main difference between SRM 2519a and its predecessor, SRM 2519, is the use of lower pressure in the hydrogen cyanide cell to produce narrower lines. Thus, SRM 2519a extends the use to higher resolution and higher accuracy applications.

**Certified Wavelength Values:** The line centers, pressure shift, and pressure broadening for 25 lines in the $H^{13}C^{14}N$ $2\nu_3$ rotational-vibrational combination band have been accurately measured at NIST, and the molecular constants of the band have been determined [1]. The certified line center for each of the 25 lines measured at NIST was determined by adding the line's pressure shift (due to collisions between HCN molecules at the 3.3 kPa pressure within the SRM cell) to the measured zero-pressure line center. The zero-pressure line centers of other lines in the band were calculated from the molecular constants of the band, and the appropriate pressure shift was derived using interpolation and extrapolation [2]. Details of the measurement procedure, data analysis, and uncertainty analysis can be found in references 1 and 2. A spectrum of the absorption band is shown in Figure 1, and certified wavelength values are given in Table 1. Figures 2 through 4 show scans near lines P10, P11, and P16. The center wavelengths of the lines listed in Table 1 are certified with uncertainties ranging from 0.04 pm to 0.24 pm. These uncertainties are the expanded uncertainties using a coverage factor $k = 2$ (i.e., our quoted uncertainty is $\pm 2\sigma$).

**Expiration of Certification:** The certification of this SRM is indefinite within the measurement uncertainties specified, provided the SRM is handled, stored, and used in accordance with the instructions given in this certificate (see "Storage and Handling").

## 4. Hyperion Interrogator specification definitions and test methodology

Micron Optics applies the following definitions and test methodologies to performance specifications on its optical sensing interrogators.

### 4.1.1. Wavelength Accuracy

Defined as "accuracy of measurement", per NIST Technical Note 1297, 1994 Edition, Section D.1.1.1, the "closeness of the agreement between the result of a measurement and the value of the measurand."

Accuracy is here reported as the standard uncertainty of the distribution of measurements made over the course several minutes, relative to the NIST Standard Reference Material 2519, as described in NIST Special Publication 260-137. Of the HCN lines characterized by NIST, those used in the qualification of MOI spectral interrogators are the 21 lines certified by NIST (or a subset thereof) with an expanded uncertainty (coverage factor *k*=2) of +/-0.0006nm.

To be consistent with the sensing and telecom industries' expectation of low distribution and low systematic error of wavelength measurements, MOI enhances its definition of wavelength accuracy to a more stringent definition that includes a component of "systematic error", defined in NIST Technical Note 1297, Section D.1.1.6. Here, "systematic error" is defined as the "mean that would result from an infinite number of the same measurand carried out under repeatability conditions minus the value of the measurand." Here, again the measurand is NIST SRM 2519.

In total, the wavelength accuracy reported for MOI spectral interrogators is the absolute value of the "systematic error" plus the standard uncertainty of the "accuracy of measurement," or $|\mu| + \sigma$ of the series of wavelength measurements made on the atomic absorption NIST Standard Reference Material 2517. In order to eliminate stability effects of peak detection which might influence the accuracy measurement, averaging of the spectrum prior to peak detection is performed.

In addition to the measurements made relative to the atomic absorption references, measurements are made on Fabry-Perot artifacts which provide spectral features across the full measurement wavelength range of the Equipment Under Test (EUT). The Fabry-Perot artifacts are characterized using a method similar to that by which NIST determines absolute wavelengths for the gas absorption SRMs (see NIST Special Publication 260-137.) By the fundamentals of operation, the Fabry-Perot elements exhibit a high degree of linearity in the frequency domain, limited to ~1pm by chromatic dispersion. This behavior is used to ensure frequency measurement linearity, and thus relative wavelength accuracy, outside of the wavelength ranges that can be measured using the NIST SRMs.

*The HCN cell operates in the following manner. Either broad spectrum or swept spectrum light is introduced to the input leg of the device. For most wavelengths, light propagates through the device with little coupling or transmission loss and emerges from the output leg unmodified. Certain specific wavelengths of light excite rotational-vibrational modes of the HCN gas, thereby converting the optical energy to thermal energy. This heat is dissipated and results in an optical "loss" at very specific wavelengths. These wavelengths are highly insensitive to temperature and are determined by the atomic properties of the gas to be consistent from sample to sample. The widths of the atomic absorption lines are sensitive to pressure but the center wavelengths of those lines are not. The HCN cells used by Micron Optics for the calibration and test of the optical sensor interrogators are well specified for gas cell pressure, and a set of matched null detection coefficients are used to ensure consistent and accuracy determination of the measured gas cell peaks.*

### 4.1.2. Repeatability

Defined as "Repeatability (of results of measurements)", per NIST Technical Note 1297, Section D.1.1.2, the "closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement," called "repeatability conditions."

"Repeatability conditions" include using the same measurement procedure, the same observer, the same measuring instrument used under the same conditions (constant temperature), the same location, and repetition over a short period of time.

In the interest of making such measurements most applicable to the users of MOI products, the test artifact selected for the repeatability test is representative of a typical sensor which might be used, of bandwidth ~0.1nm, high reflectivity. Repeated measurements are made on the artifact by the EUT over the course of minutes, and the standard uncertainty (1 σ distribution) of the resulting measurements is reported as the Repeatability.

In order to address multiple likely applications, the repeatability may be reported at multiple data rates or averaging conditions (e.g. @ 250 Hz with no averaging, or at 10Hz with 25 averages per data point.)

#### 4.1.3. Stability

In order to enhance the utility of the accuracy and repeatability specifications, a specification called stability has been added. The stability specification captures effects of operating temperature and longer term testing of the EUT, involving a minimum of one thermal cycle over the operating temperature of the device.

The measurement for stability involves capturing data on an artifact of sufficient stability with optical features that cover the full measurement wavelength range of the EUT, such as a Fabry-Perot etalon. The agreement between successive measurements is recorded over wavelength, time, and temperature. The resulting 1 σ distribution is calculated and reported as the stability of the EUT.

In the measurements and calculations used for computing the stability parameter, no data averaging is employed.

*In the AFPI design, the two mirrored sections are separated by a special glass material that is engineered to have very little mechanical expansion with changes in ambient temperature (low CTE). This mirror and low CTE spacer assembly is packaged with input and output coupling lenses into a hermetically sealed package that maintains a constant pressure and gas constituency in the cavity. With no significant thermal expansion or change in gas pressure the resonant frequencies of the devices are very stable.*

*The Fabry-Perot artifacts are characterized using a method similar to that by which NIST determines absolute wavelengths for the gas absorption SRMs (see NIST Special Publication 260-137.) By the fundamentals of operation, the Fabry-Perot elements exhibit a high degree of linearity in the frequency domain, limited to ~1pm by chromatic dispersion. The AFPI reference frequency is qualified to have stability of +/- 5pm or over the operating temperatures of 0 to 70 degrees C. With such an absolute reference frequency stability, the stability of the FSR is ~2000 times greater for an AFPI of FSR ~100GHz (FSR*mode # = peak frequency; 100GHz * 1940 = 194THz = 1545nm). As such, the AFPI acts as a highly precise relative wavelength reference and is used in combination with the NIST traceable HCN cell to provide a full wavelength range referencing system.*

*Though the AFPI test artifacts have been designed, built and qualified to Telcordia FR-2883 standards and are expected to have a minimum 20 year operational lifetime, they are not themselves a directly NIST traceable wavelength reference. However, the following process allows Micron Optics to extend the traceability of the NIST cell to the AFPI component for use as a secondary reference.*

*MOI has a designated "master" sm125 module that is responsible for calibration of all of the AFPI test artifacts used in the manufacturing and FFT processes. This unit is itself subject to a scheduled recalibration. Every four weeks, the master module (with internal NIST-traceable Acetylene atomic absorption gas cell) is recalibrated to an external NIST traceable HCN cell. This process re-affirms that the internal gas cell and calibration parameters are correct for this master module.*

*Once calibration is confirmed against both internal and external NIST cell or the master module, the AFPI test artifacts can be scanned by the master module and reference peak wavelengths recorded. The new set of reference peaks for the AFPI reference is compared against the previously recorded set of AFPI peak values from the previous scheduled AFPI reference certification (performed internally every two weeks). A comparison between the "new" values and the "old" values is made, and all measured reference peaks must agree within a 1.5 pm maximum across the full wavelength range. This 1.5 pm limit includes any changes that result from AFPI drift, master module calibration differences, and any peak detection algorithm induced offsets.*

*If the new traces agree with the old traces within 1.5 pm, then the AFPI reference is considered to be stable and is re-introduced into the manufacturing process with an update "expiration date" (of two weeks) past the calibration. If the device does NOT agree with the previous measurements, then an investigation of that reference is opened, typically* *comparing the results of other AFPI recalibrations. If failed AFPI is alone in its failure, it is concluded that the reference is instable and is removed from the AFPI reference "pool". If multiple references fail the recalibration, it is indicative of a process error involving the master sm125 NIST traceable calibration. (NOTE: there has not been to date a multiple AFPI/calibration process failure).*

*Thus, the combination of NIST traceable sm125 calibrations with AFPI stability requirements ensures that the AFPI reference population provides a stable and reliable collection of full wavelength reference artifacts with a traceability path to a primary NIST traceable standard. However, although the references are assured measurements stability within 1.5 pm, the AFPI references themselves are NEVER used to determine the "absolute" wavelength performance of any Micron Optics interrogator. Absolute wavelength measurements are exclusively performed on NIST traceably HCN reference cells. The stability of the AFPI modules do however allow for convenient wavelength linearity and stability measurements during the FFT and Burn-in processes, respectively.*

#### 4.1.4. Resolution

To be derived by user for specific applications based upon stability and repeatability specifications.

#### 4.1.5. Reproducibility

Defined as "reproducibility (of measurement results)", per NIST Technical Note 1297, Section D.1.1.3, the "closeness of agreement between the results of measurements of the same measurand carried out under changed conditions of measurement."

Here, the "changed conditions" include a different observer, measurement instrument, or time. In principle, this specification is intended to ensure that a given measurand could be measured by multiple MOI spectral interrogators using the same data analysis tools at different times and by different users, and achieve measurement results that are consistent within the reproducibility specification.

In order to quantify the reproducibility of measurements from a particular class of instruments, a complete wavelength accuracy analysis is made on each, and a mean "error of measurement" is calculated. This "error of measurement" is defined by NIST Technical Note 1297, Section D1.1.4, the error (of measurement)", and is measured relative to NIST SRM 2519. The reproducibility is then defined as the standard deviation of the set of "error" measurements across a sample of measured instruments.