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OTDR calibration method using multiple levels of optical fiber backscatter

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Abstract

This paper describes a novel approach to Optical Time-Domain Reflectometer calibration which relies on an intrinsic physical property of optical fiber, the backscatter coefficient. In this procedure, multiple backscatter levels are created using increasingly long pulses of light. Each level is compared to the lowest backscatter recorded and then stored as a height, H. Accurate knowledge of the backscatter coefficient then allows theoretical Return Loss values to be computed for each backscatter level. Multiple calibration points, based on the different backscatter levels and ranging from $\sim$55 to 75dB of Return Loss, are used to produce a curve which expresses RL as a function of H. This new approach presents a method for eliminating the typical requirement of external artifacts during OTDR Return Loss calibration and increases accuracy in the typical non-linear range (RL > 60dB).

Keywords

OTDR — Backscatter — Return Loss — Calibration

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1. Background

Long and short range fiber-optic telecommunication networks are critical for supporting the ever increasing bandwidth requirements of the Internet. The performance and reliability of such networks are highly dependent on the quality of cable assemblies of which they are comprised. As fiber-to-the-home (FTTH) becomes more prevalent, the performance of short fiber patch cables, which connect fiber backbones to individual homes through a multiplexer, becomes increasingly important. Light reflected back to the source can deteriorate the quality of the signal and increase the signal-to-noise ratio[1]. Therefore, cable assemblies need to be produced with the highest amount of Return Loss (RL). To make sure the cables meet those high standards, manufacturers use a variety of testing methods and equipment to measure the losses associated with individual cables and connectors[2]. This paper focuses on Optical Time-Domain Reflectometry (OTDR) and how to accurately and reliably calibrate RL measurements.

OTDR devices work by sending a short pulse of intense light through an optical fiber, while a photo-detector examines light returning via reflections within that fiber. The timing of the photodetector's readings is converted to a distance from the source and is displayed as a trace of amplitude versus distance[3]. Fresnel reflections, arising from discontinuities in the cable assembly, cause peaks which rise above the background light level created by Rayleigh backscattering in the fiber. The height of the peaks above the backscatter level are used to calculate the RL of discontinuities[1].

Previous OTDR calibration methods have relied on having a known RL standard to compare against[4]. In this paper, we propose a novel method of RL calibration which relies instead on an intrinsic, measurable quantity of optical fiber, the backscatter coefficient (B_{ns}). While there are multiple ways of obtaining B_{ns}, this paper will focus on one method which lends itself well to lab measurements and statistical analysis. We will then detail the full calibration method once B_{ns} is determined. The final result is an RL calibration procedure that is independent of any external artifact and can be easily performed outside of laboratory environments.

2. Measuring the Backscatter Coefficient

The backscatter coefficient, B_{ns}, represents the amount of backscattered light produced by a $1ns$ pulse. The final calibration requires the accurate measurement of B_{ns} for the single-mode fiber inside the OTDR device. Fiber manufacturers supply generic values, but it was shown[3] that the uncertainty associated with these values is too large for an accurate RL calibration. Furthermore, B_{ns} is typically only provided by fiber manufacturers for two wavelengths (1310nm and 1550nm[1]). Multiple methods for measuring B_{ns} have been derived[3] to achieve the accuracy necessary for a reliable calibration. The method chosen here is an attenuated glass-to-air reflection due to its ease of measurement in laboratory environments with a large number of OTDR devices providing the needed accuracy with proper statistical analysis.

2.1 Attenuated Glass-to-Air Reflection

The attenuated glass-to-air method relies on having a known reflection peak with an RL value that falls within the linear response region of the OTDR. To get this known RL value, an attenuator is spliced in front of a UPC connector or a cleaved fiber (see Fig. 1). This attenuated glass-to-air interface is spliced to one output of a 50/50 splitter. The other output is spliced to a spool of single-mode fiber (SMF-28e, *Corning*) to measure the loss through the input connection. The loss through the attenuated branch of the splitter is measured using a powermeter. The RL of the attenuated glass-to-air reflection is calculated as

$$RL(\lambda) = RL_{cleave}(\lambda) + 2 \times loss(\lambda) \tag{1}$$

where $RL_{cleave}(\lambda)$ is the RL of a cleaved fiber (angle $< 0.1°$) for a given wavelength λ given by Eqn.4. Once this device is put together, a trace is produced using a commercially available OTDR (MS12-3050-09FA and MS12-0406-09FA, *JGR Optics Inc.*). The height of the peak, relative to the internal injection level of the OTDR, is then recorded.

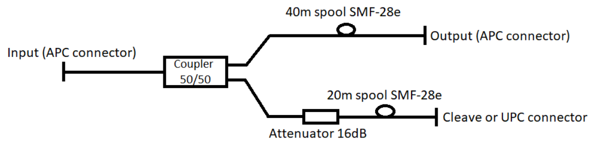

Figure 1. Diagram of a device producing an attenuated glass-to-air reflection around 55dB. The height H used in Eqn.2 and 3 is calculated by measuring the height of the peak minus the internal backscatter level of the OTDR device.

It can be shown[3] that the Return Loss value of a peak on an OTDR trace is given by Eqn.2

$$RL(H,\lambda) = B_{ns}(\lambda) - 10\log_{10}\left((10^{H/5} - 1)\cdot W\right) \tag{2}$$

where H is the peak height above the backscatter level in dB and W is the OTDR pulse width in nanoseconds[3]. Rearranging, we get

$$B_{ns} = RL + 10\log_{10}\left((10^{H/5} - 1)\cdot W\right) \tag{3}$$

where RL is the previously calculated RL in dB of the attenuated glass-to-air interface reflection.

We performed B_{ns} measurements of the same attenuated glass-to-air interface with 75 different commercial OTDRs (MS12-3050-09FA, *JGR Optics Inc.*). The measured values of B_{ns} followed a normal distribution with a standard deviation of 0.4dB.

2.2 Uncertainty on the Backscatter Coefficient

The calibrated RL measurement accuracy is highly dependent on the accuracy of B_{ns}. It is therefore necessary to examine the error associated with the attenuated glass-to-air reflection method.

When calculating the RL associated with the attenuated glass-to-air reflection of the apparatus shown in Fig. 1, Fresnel's equation is used to determine the 14.4dB value at the interface. A perfect cleave angle of 0° is assumed. This gives us Eqn.4[5] .

$$RL = \left(\left|\frac{n_1 - n_2}{n_1 + n_2}\right|^2\right)$$

$$RL_{dB} = -10\cdot\log_{10}\left(\left|\frac{n_1 - n_2}{n_1 + n_2}\right|^2\right) \tag{4}$$

Consider an error of ± 0.5 deg. Using the complete Fresnel's formula[5], it can be shown this results in an RL error of 0.001dB (<0.01%) and is therefore negligible. Using a modern cleaver and the angle measurement tool of a modern splicer, a cleave angle that is less than 0.5° is easily achievable.

The second quantity used to calculate the RL of the apparatus is the loss through the system. This is done using a calibrated powermeter which, in our case, has a relative power measurement accuracy of ±0.15dB. Since Eqn.1 uses the system loss twice, we get a total uncertainty on our system loss measurement of ±0.30dB.

The height H of the interface peak is obtained by subtracting the injection level from the height of that peak. The uncertainty of H is mainly dependent on the uncertainty of the injection level.[2]. That level is calculated by taking the average of the trace corresponding to a $20m$ spool of SMF-28e fiber located inside the OTDR. Repeating the same measurement 30 times with a single device (see Fig. 2), it was found that the standard deviation (σ) of the averages was ±0.01dB. We define the uncertainty on the injection level as 3σ, which encompasses 99.73% of all possible injection levels for this

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[1] These are the predominant wavelengths used for fiber-optic cable assembly qualification; however, other wavelengths are often required, especially as WDMs become more widely used.

[2] Peaks significantly higher (> 1dB) than the backscatter level on an OTDR are extremely stable and thus the repeatability of the peak height is negligible when compared to the injection level average repeatability.

OTDR. Therefore, the uncertainty is ±0.03dB. Using Eqn.2, we can see that increasing or decreasing H by 0.03dB results in a difference in RL of ±0.06dB when RL is around 55dB.

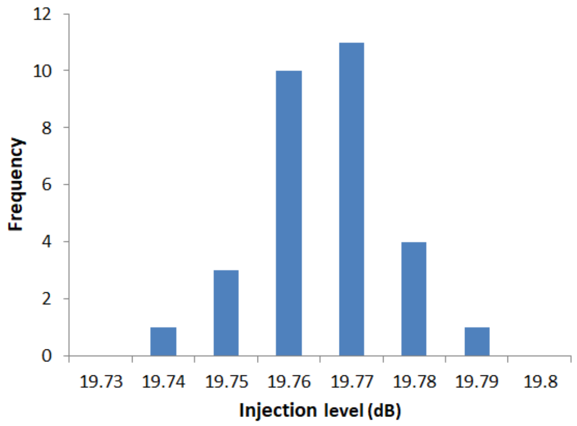

Figure 2. Distribution of 30 measurements of the injection level of a single OTDR device. Injection levels are calculated by taking the average of the trace produced by a 20m spool of optical fiber.

Finally, the pulse widths used need to be accurately measured. Using an oscilloscope (MSO4102B, *Tektronix*), we can measure to an accuracy of ±10ps. Using Eqn.2, we calculate a B_{ns} uncertainty due to the pulse width accuracy of ±0.006dB. The resulting total uncertainty is ±0.367dB.

3. Calibration Procedure

Typical OTDRs either use an internal RL reference[6] or Eqn.2 to calculate RL from a peak on the OTDR trace[4]. Both methods produce a response curve that is linear for RL less than 60dB. However, the two methods become non-linear for RL greater than 60dB[3]. Common calibration procedures rely on a single adjustment point near 55dB to offset Eqn.2. Instead, we propose a calibration process that produces an RL vs H curve from multiple RL points spanning 55 to 75dB. This results in the OTDR device being more precisely calibrated in its non-linear region.

3.1 Producing Different Injection Levels

The first part of the calibration procedure consists of creating increasingly long pulses with the OTDR to produce backscatter levels (or injection levels) of increasing amplitude with respect to the measurement pulse width (D_m).

1. Set the OTDR pulse width to the minimum value available, D_m. In our case we were able to obtain a stable 5ns pulse from the JGR Optics RL1-3456-09FA.

2. Capture an OTDR trace and measure the backscatter level of a sufficiently long spool of optical fiber inside the instrument. The calculated level value is the average of the trace for the last 20m of fiber before the output.

3. Repeat the above step for several increasingly large pulse widths (D_i). In our case, we used 7, 10, 20, 50, 100 and 200 nanosecond pulses.

4. The differences in height, H_i, between the different backscatter levels generated by each D_i with respect to the level generated by D_m is recorded.

3.2 Equating Injection Levels to Return Loss

The heights H_i represent the backscatter produced by a pulse (D_i) exceeding the backscatter produced by D_m (B_m) (shaded parts in Fig. 3). We define this excess backscatter as B_i.

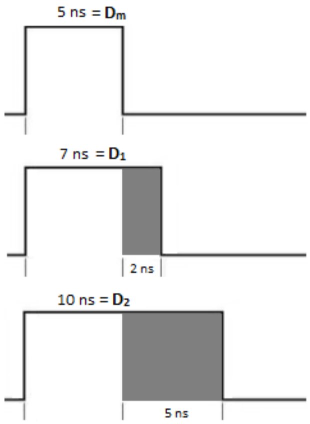

Figure 3. Representation of the excess backscatter produced by different pulse widths with respect to D_m.

Suppose a peak P of height H_p above the injection level IL_m is produced from a pulse of width D_m and an injection level IL_i of height H_i above IL_m from a pulse of width D_i (Fig. 4).

On an OTDR trace, the signal's amplitude is a function of the number of photons hitting the photodetector. Therefore, when $H_P = H_i$ the amount of light returning to the photodetector is equal for both traces at distance x. Therefore, the RL of P equals the excess backscatter B_i produced by D_i compared to D_m (Eqn. 5).

$$\begin{aligned} &\text{when } H_P = H_i \\ &RL(H_P) = B_i(D_i - D_m) \end{aligned} \tag{5}$$

For narrow pulses (smaller than 2μs), the backscatter produced is proportional to the pulse width [7]. Since pulse widths are usually measured in duration and not physical width, the calculations can be simplified by taking advantage of the backscatter produced by a square 1ns pulse at a wavelength λ. This is defined as the backscatter coefficient Bns(λ). It can be shown that for a pulse of width T, the total backscatter produced is equivalent to the summation of T 1-ns pulses [7].

Using the following equation, we can calculate an amount of excess backscatter B_i produced by a pulse of width D_i

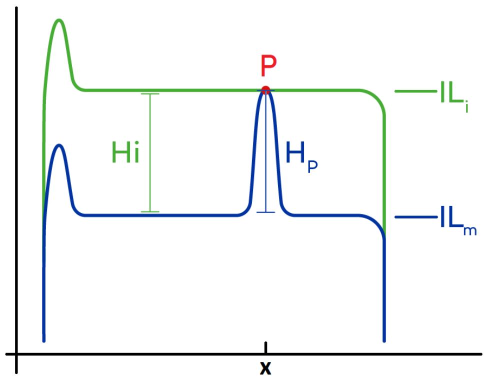

Figure 4. Graphical representation of Eqn. 5 where the condition is met at distance x.

compared to D_m

$$B_i(\lambda) = -10 \cdot \log_{10}\left((D_i - D_m) \cdot 10^{B_{ns}(\lambda)/10}\right) \qquad (6)$$

We now have a way of associating a pulse width difference $(D_i - D_m)$ in ns to an amount of backscatter B_i in dB. Each height H_i measured from $D_i - D_m$ is then associated to a B_i value representing the RL value of a peak of height H above the injection level. Table 1 shows an example of such calibration points produced using a JGR Optics RL1-3456-09FA with a D_m of 5.3ns. These points allow us to produce a calibration curve equating a peak height H_i above the injection level to an RL value using B_{ns}=78dB at 1310nm. A calibration curve is required for each wavelength.

index i	Pulse width, D (ns)	Height difference, H (dB)	B (dB)
1	7.1	0.49	75.33
2	10.0	1.23	71.22
3	20.2	2.72	66.27
4	50.2	4.69	61.48
5	100.2	6.15	58.22
6	200.2	7.63	55.10

Table 1. Injection level height differences (H) for various pulse widths (D) with respect to the measurement pulse width (D_m) at 1310nm. Each height difference is equivalent to the backscatter level (B) produced by a pulse of duration $D - D_m$.

In the event the OTDR needs to test longer cables where a higher dynamic range is needed, a calibration curve can be produced using a longer pulse as its D_m.

If $D_i - D_m$ is greater than 2μs, the physical length of the pulse in the fiber is long enough that we need to take into account the loss associated to the optical fiber transmission within the length of the pulse. The following formula should then be used to calculate B_i[3]

$$B_i(\lambda) = 10 \cdot \log_{10}\left(\frac{2\alpha(\lambda)\cdot\Delta x}{1 - e^{-2\alpha(\lambda)\cdot(D_{\Delta x}\cdot(D_i - D_m))}}\right) - B_{ns}(\lambda) \quad (7)$$

where $\alpha(\lambda)$ is the linear attenuation coefficient of the fiber (1/km) at wavelength λ, Δx is 0.0001km (the physical length of a 1-ns pulse on an OTDR trace) and $D_{\Delta x}$ is 0.0001km/ns. Eqn.6 and Eqn.7 are equivalent for short pulses ($< 2\mu$s) and can be used interchangeably. These two equations are valid when square pulses are produced.

3.3 Extending the Calibration Curve

Using multiple backscatter levels obtained from 7ns to 200ns pulses gives us a range of RL calibration from 55dB to 75dB. In this range, an interpolation function is used between the discrete calibration points. Outside this range, we use Eqn.2. For a height H greater than the last (or N^{th}) calibration point or smaller than the first calibration point, we use Eqn.2. However, to ensure that we have a properly adjusted curve (i.e. no discontinuities), we need to offset Eqn.2 outside of the calibration points. To get the offsets at the 1^{st} and N^{th} calibration point, we substract Eqn.2 and 6.

$$Off(H,\lambda) = \begin{cases} RL(H_1,\lambda) - B_1(\lambda) & H<H_1 \\ RL(H,\lambda) - \text{interpolation}\langle H_i,B_i\rangle(H,\lambda) & H_1<H<H_N \\ RL(H_N,\lambda) - B_N(\lambda) & H>H_N \end{cases} \qquad (8)$$

The fully calibrated response curve is:

$$RL_{cal}(H,\lambda) = RL(H,\lambda) + Off(H,\lambda) \qquad (9)$$

where $RL(H,\lambda)$ is calculated with Eqn.2.

Using the data from Table 1 with Eqn.8 and 9, we can come up with a calibration curve for the whole dynamic range of the unit. Fig. 5 shows the calibration curve obtained from this example. The indent figures shows the offset between Eqn.8 and 9 for a RL range of 30-90dB. As the figure shows, the offset is not a constant value throughout the range.

4. Discussion

4.1 Pulse Shape Error

The calibration procedure described in the previous section solves the problem of the need for an external artifact when calibrating an OTDR. It relies on intrinsic properties of optical fiber and uses the difference between injection levels on an OTDR trace to produce calibration points and adjust the RL equation. Unlike current calibration methods, multiple points are used to correct the theoretical OTDR response curve. This allows for a more accurate RL measurement especially in the non-linear part of the response curve. However, this novel technique assumes a square pulse shape.

If we have a rounded pulse (which is often the case for short pulses, though this largely depends on the laser and driving electronics), we must calculate the width of a square pulse having energy equal to the rounded pulse with a measured full width at half maximum (FWHM). This energy is represented by the area under the curve formed by the pulse when measured in the time domain. The maximum value of the pulse curve is used to normalise its integral. Thus we are

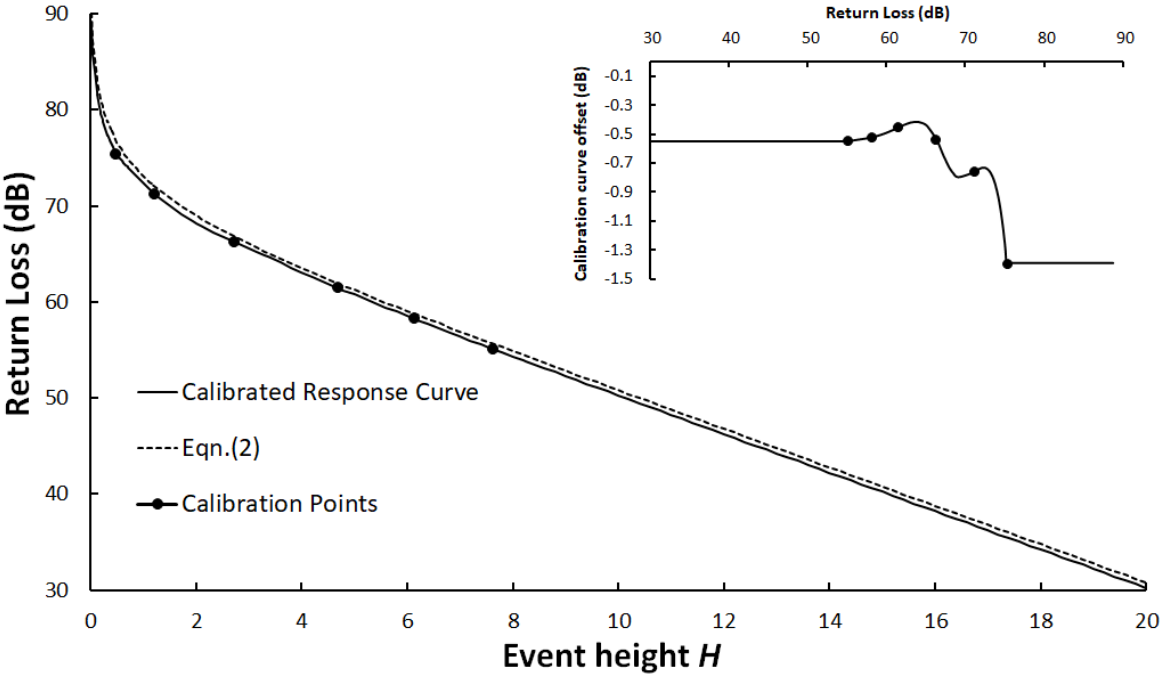

Figure 5. Calibration curve obtained from the data in Table 1 at 1310nm. The indent figure is the offset between the calibrated curve and the OTDR formula using the same D_m and B_{ns}.

able to calculate the equivalent width of a square pulse with the same maximum power level as the original rounded pulse. The correction factor is obtained by calculating the ratio of the measured FWHM to the equivalent square pulse width. This correction factor is almost always required as no generated pulse is perfectly square. Any pulse rounding not accounted for will add to the uncertainty of the calibration.

4.2 Calibrated RL Accuracy

The accuracy of an RL measurement using an OTDR-based meter can be divided in two different parts which, when combined, properly assess the total accuracy of the measurement: uncertainty and repeatability of the measurement.

Calibration Point Uncertainty

Each calibration point is calculated from the difference in height of two injection levels produced with different pulse widths. In Fig. 2, we showed the distribution of 30 measurements of the injection level of a single OTDR device. The 3σ confidence interval of this distribution leads to an uncertainty of $\pm$ 0.03dB on the injection level. As we are using two levels to calculate H, the total uncertainty of a calibration point doubles to $\pm$ 0.06dB.

Since the uncertainty of a calibration point is with respect to the value H, we need to use Eqn.9 to convert to RL uncertainty values. It is then possible to calculate the uncertainty of our calibration curve in dB at specific RL values[3]. Finally, we add the uncertainty of B_{ns} ($\pm$ 0.4dB) to get the total uncertainty of a measurement.

RL Measurement Repeatability

Between measurements of a single RL event, the only variable in Eqn.9 is H. As mentioned in Section 2.2, we consider the fluctuation in peak height to be negligible compared to the repeatability of the injection level average. We can therefore use the $\pm$ 0.03dB uncertainty previously calculated in Section 2.2.

To transform the repeatability of H into a usable RL value, we use Eqn. 9. A fixed variation in H corresponds to different RL repeatability depending on the range, as shown in Table 2.

RL Range (dB)	Accuracy (dB)
30 to 70	± 1.0
70 to 75	± 1.3
75 to 80	± 2.9
80 to 85	± 3.9

Table 2. Total accuracy (includes uncertainty and repeatability) for different RL ranges. The accuracy for a given range is calculated at the upper limit of that range.

5. Conclusion

Any user working with fiber optics test equipment on a daily basis knows that they need to have their equipment calibrated

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[3] Since our calibration curve is not linear, the uncertainty depends on the value of H and is not constant for the whole dynamic range of RL measurements.

at regular intervals (usually once every year) to ensure optimal performance. This, unfortunately, means that a production station will have down-time when the meter has to go back to an accredited calibration lab. On top of the loss of production time, there are costs associated with this process. Users might be tempted to build their own artifact and calibrate their units themselves, thus, saving a lot of time and money in the process.

Unfortunately, many problems can arise from an out-of-lab calibration. As mentioned in section 2, the actual RL of the artifact depends on the losses within it and the connections made to its output fibers, which are prone to contamination and mating adapter uncertainties.

The backscatter calibration method proposed here removes the persistent requirement of external reflectance artifacts during RL calibration processes. Using the standard OTDR equation, a length of internal fiber whose backscatter coefficient (B_{ns}) is known and the ability to generate various pulse widths, an accurate and reliable RL calibration can be performed.

A big advantage of this procedure is that it is easily automated once the pulsewidths have been accurately measured. Since this step is usually done during manufacturing, an end-user can easily follow the automated procedure provided by the manufacturer and complete the calibration of the unit. This feature reduces significantly the down-time and cost associated with annual calibration by a certified calibration laboratory.

The accuracy of this calibration procedure relies on an accurate determination of B_{ns}. Several different approaches exist to calculate this critical value. We showed the use of one such approach applied in a rigorous manner to achieve a statistically significant result. An alternative method would be direct measurement of the required parameters (i.e numerical aperture, attenuation coefficient and refractive index) with high accuracy.

Performing these direct measurements would require extensive collaboration with fiber manufacturers, who also happen to be the end users of OTDR measurement equipment. This presents an opportunity for the fiber-optic cable industry to consolidate and standardize its Return Loss measurement and reporting procedures. As Internet bandwidth and end user requirements continue to increase, it is imperative that test instruments continue improving to keep pace.

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