

Units, Traceability, and Calibration of Optical Instruments

Andreas Gerster

This article presents a short and comprehensive overview of the art of units measurement and calibration. Although the examples focus on optical instruments, the article may be of interest to anyone interested in metrology.

The increasing number of companies using quality systems, such as the ISO 9000 series, explains the growing interest in the validation of the performance of measurement instruments. For many customers it is no longer sufficient to own a feature-rich instrument. These customers want to be sure that they can test and measure in compliance with industrial and legal standards. Therefore, it is important to know how it can be guaranteed that a certain instrument meets specifications.

This article is intended to give an overview of the calibration of optical power meters and other optical instruments at HP. Along with the specific instruments, common processes and methods will be discussed. The first section will deal with some aspects of the theory of measurement. Then, processes and methods of calibration and traceability will be discussed. These first two sections give a general and comprehensive introduction to the system of units. Finally, the calibration procedures for certain HP optical instruments will be described.

Theory of Measurement

Measurement has long been one of the bases of technical, economical, and even political development and success. In the old Egyptian culture, surveying and trigonometry were important contributors to their prosperity. Religious and political leaders in these times founded their power on, among other things, the measurement of times and rotary motions, which allowed them to predict solar and lunar eclipses as well as the dates of the flood season of the Nile river. Later in history, weights and length measurements were fundamental to a variety of trading activities and to scientific progress. Improvements in



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measurement techniques, for example, allowed Kepler to set up his astronomical laws. Kepler used the measurement results of his teacher Tycho Brahe, who determined the orbits of the planets in the solar system with an unprecedented accuracy of two arc minutes.¹ Because of the strong impact of a homogenous system of measurements, all metrologic activities even today are controlled by governmental authorities in all developed countries.

Let us consider first the measurement itself. Measurement is the process of determining the value of a certain property of a physical system. The only possibility for making such a determination is to compare the unknown property with another system for which the value of the property in question is known. For example, in a length measurement, one compares a certain distance to the length of a ruler by counting how often the ruler fits into this distance. But what do you use as a ruler to solve such a measurement problem? The solution is a mathematical one: one defines a set of axiomatic rulers and deduces the practical rulers from this set.

At first, rulers were derived from human properties. Some of the units used today still reflect these rulers, such as feet, miles (in Latin, *mille passuum* = 1000 double steps), cubits (the length of the forearm), or seconds (the time between two heartbeats is about one second). As one can imagine, in the beginning these axiomatic rulers were anything but general or homogenous—for example, different people have different feet. Only a few hundred years ago, every *Freie Reichsstadt* (free city) in the German empire had its own length and mass definitions. The county of Baden had 112 different cubits at the beginning of the nineteenth century, and the city of Frankfurt had 14 different mass units.² In some cities the old axiomatic ruler was mounted at the city hall near the marketplace and can still be visited today.

With the beginning of positivism, about the time of the revolution in France, people were looking for absolute types of rulers that could make it easier to compare different measurements at different locations. Thus, in 1790, the meter was defined in Paris to be 1/40000000 of the length of the earth meridian through Paris. Because such a measurement is difficult to carry out, a physical artifact was made out of a special alloy, and the standard meter was born. This procedure was established by the international treaty of the meter in 1875, and although the

unit definitions have changed, the contract is still valid today.

Related to this search for suitable axiomatic rulers is the question of how many different rulers are really necessary to deduce all practical units. Among others, F. Gauss delivered valuable contributions to the answer. He proposed a system consisting of only three units: mass, time and length. All other mechanical and electrical and therefore optical units could be deduced. As Lord Kelvin showed in 1851, the temperature is also directly related to mechanical units. Therefore, along with the meter, two other axiomatic rulers were defined. Mass was defined by the international kilogram artifact which was intended to have the mass of one cubic decimeter of pure water at 4°C (in fact it was about 0.0028 g too heavy). The definition of time finally was related to the duration of a certain (astronomical) day of the year 1900.

For various reasons, these definitions were not considered suitable anymore in the second half of the 20th century, and metrologists tried to find natural physical constants as bases for the definition of the axiomatic units. At first the time unit (second) and the length unit (meter) were defined in terms of atomic processes. The meter was related to the wavelength of the light emitted from krypton atoms due to certain electronic transitions. In the case of the time unit, a type of cesium oscillator was chosen. The second was defined by 9,192,631,770 cycles of the radiation emitted by electronic transitions between two hyperfine levels of the ground state of cesium 133.

These new definitions of the axiomatic units had a lot of advantages over the old ones. The units of time and length were now related to natural physical constants. This means that everybody in the world can reproduce these units without having to use any artifacts and the units will be the same at any time in any place.

For practical reasons, more units were added to the base units of the *Système International d'Unités*, or International System of Units (SI). Presently there are seven base units, two supplementary units, and 19 derived units in the SI. The base units are listed in **Table I**. There is no physical necessity for the selection of a certain set of base units, but only practical reasons. In fact, considering the definitions, only three of the base units—the second, kelvin, and kilogram—are independent, and even the kelvin can be derived from mechanical units.

Table I

Definitions of the Seven Base Units of the Système International d'Unités (SI)

Unit	Name and Symbol	Definition
Length	meter (m)	One meter is now defined as the distance that light travels in vacuum during a time interval of 1/299792458 second.
Mass	kilogram (kg)	The kilogram is defined by the mass of the international kilogram artifact in Sèvres, France.
Time	second (s)	A second is defined by 9,192,631,770 cycles of the radiation emitted by the electronic transition between two hyperfine levels of the ground state of cesium 133.
Electrical Current	ampere (A)	An ampere is defined as the electrical current producing a force of 2×10^{-7} newtons per meter of length between two wires of infinite length.
Temperature	kelvin (K)	A kelvin is defined as 1/273.16 of the temperature of the triple point of water.
Luminous Intensity	candela (cd)	A candela is defined as the luminous intensity of a source that emits radiation of 540×10^{12} hertz with an intensity of 1/683 watt per steradian.
Amount of Substance	mole (m)	One mole is defined as the amount of substance in a system that contains as many elementary items as there are atoms in 0.012 kg of carbon 12.

Nevertheless, some small distortions remain. Of course, all measurements are influenced by the definitions of the axiomatic units, and so the values of the fundamental constants in the physical view of the world, such as the velocity of light c , the atomic fine structure constant α , Plank's constant h , Klitzing's constant R , and the charge of the electron e , have to be changed whenever improvements in measurement accuracy can be achieved.

This has led to the idea of relating the axiomatic units directly to these fundamental constants of nature.³ In this case the values of the fundamental constants don't change anymore. The first definition that was directly related to such a fundamental constant of nature was the meter. In 1983 the best known measurement value for the velocity of light c was fixed. Now, instead of changing the value for c whenever a better realization of the meter is achieved, the meter is defined by the fixed value for c . One meter is now defined as the distance that light travels in a vacuum during a time interval of 1/299792458 second. The next important step in this direction could be to hold the value e/h constant and define the voltage by the Josephson effect (see the Appendix).

Calibration and Traceability

According to an international standard, calibration is "the set of operations which establish, under specified conditions, the relationship between the values indicated by the

measuring instrument and the corresponding known values of a measurand."⁴ In other words, calibration of an instrument ensures the accuracy of the instrument.

Of course, no one can know the "real" value of a measurand. Therefore, it must suffice to have a best approximation of this real value. The quality of the approximation is expressed in terms of the uncertainty that is assigned to the apparatus that delivers the approximation of the real value. For calibration purposes, a measurement always consists of two parts: the value and the assigned measurement uncertainty.

The apparatus representing the real value can be an artifact or another instrument that itself is calibrated against an even better one. In any case, this best approximation to the real value is achieved through the concept of *traceability*. Traceability means that a certain measurement is related by appropriate means to the *definition* of the unit of the measurand under question. In other words, we trust in our measurement because we have defined a unit (which is expressed through a standard, as shown later), and we made our measurement instrument conform with the definition of this unit (within a certain limit of uncertainty).

Thus, the first step for a generally accepted measurement is a definition of the unit in question that is accepted by everybody (or at least by all people who are relevant for our business), and the next step is an apparatus that can

realize this unit. This apparatus is called a (primary) *standard*. What does such an apparatus look like? It simply builds the definition in the real world. In the case of the second, for example, the *realization* of the unit is given by cesium atoms in a microwave cavity, which is used to control an electrical oscillator. The realization of the second is the most accurate of all units in the SI. Presently, uncertainties of 3×10^{-15} are achieved.⁵ The easiest realization is that of the kilogram, which is expressed by the international kilogram artifact of platinum iridium alloy in Sèvres near Paris. The accuracy of this realization is excellent because the artifact *is* the unit, but if the artifact changes, the unit also changes. Unfortunately, the mass of the artifact changes on the order of 10^{-9} kg per year.⁵

Representation and Dissemination

National laboratories (like PTB in Germany or NIST in the U.S.A.) are responsible for the realization of the units in the framework of the treaty of the meter. Since there can be only one institution responsible for the realization, the national laboratories must disseminate the units to anyone who is interested in accurate measurements. Most of the realizing experiments are rather complicated and sometimes can be maintained for only a short time with an appropriate accuracy. Thus, for the *dissemination* of the unit, an easy-to-handle *representation* of the unit is used. These representations have values that are traceable to the realizing experiments through *transfer measurements*. New developments in metrology allow the representation of some units as quantum standards, so in some cases the realization of a unit has a higher uncertainty than its representation. In the Appendix this effect is discussed for the example of electrical units.

Once the representation of a unit is available, the calibration chain can be extended. The representations can be duplicated and distributed to institutions that have a need for such secondary standards. In some cases, a representation can be used directly to calibrate general-purpose bench instruments. In the case of electrical units, the representations are used to calibrate highly sophisticated calibration instruments, which allow fully automatic calibration of a device under test, including the necessary reporting.⁶

Although the calibration chain described above is a very common and the most accepted method of providing

traceability, it is only one among others. Another method of providing traceability involves comparing against natural physical constants. A certain property of a physical system is measured with the device under test (DUT) and the reading of the device is compared against the known value of this property. For example, a wavelength measurement instrument can be used to measure the wavelength of the light emitted from a molecule as a result of a certain electronic transition. The reading of the instrument can easily be compared against the listed values for this transition. This method of providing traceability has some advantages. It is not necessary to have in-house standards, which have to be recalibrated regularly, and in principle, the physical constant is available everywhere in the world at all times with a fixed value. However, a fundamental issue is to determine what is considered to be a natural physical constant. Of course there are the well-known fundamental constants: the velocity of light, Planck's constant, the hyperfine constant, the triple point of water, and so forth, but for calibration purposes many more values are used. In literature some rather complicated definitions can be found.³ We'll try a simple definition here: a natural physical constant is a property of a physical system the value of which either does not change under reasonable environmental conditions or changes only by an amount that is negligible compared to the desired uncertainty of the calibration. Reasonable in this context means moderate temperatures (-50 to 100°C), weak electromagnetic fields (order of milliteslas), and so forth.

Somewhat different from the two methods described above are ratio-type measurements using self-calibrating techniques. An example of this technique will be described in the next section.

Calibration of Optical Instruments

In this section we describe the calibration procedures and the related traceability concepts of some of the optical measurement instruments produced by HP. In contrast to the calibration of electrical instruments like voltmeters, it is nearly impossible to find turnkey solutions for calibration systems for optical instruments. Because optical fiber communications is a new and developing field, the measurement needs are changing rapidly and often the standardization efforts cannot keep pace.

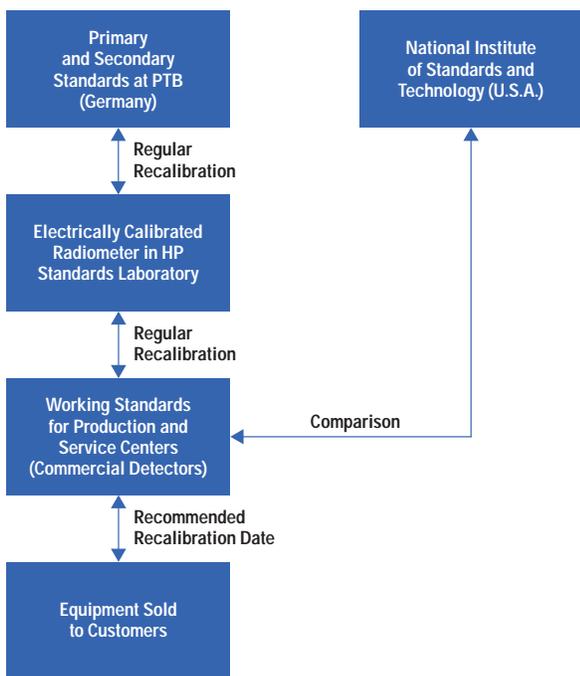
Calibration of Optical Power Meters

The basic instrument in optical fiber communications is the optical power meter. Like most commercial power meters used for telecommunications applications, the HP 8153A power meter is based on semiconductor photodiodes. Its main purpose is to measure optical power, so the most important parameter is the optical power accuracy.

Figure 1 illustrates the calibration chain for HP's power meters. This is an example of the traceability concept of an unbroken chain of calibrations. It starts with the primary standard at the Physikalisch Technische Bundesanstalt (PTB) in Germany. As discussed in the previous sections, the chain has to start with the definition of the unit. Since we want to measure power, the unit is the watt, which is defined to be $1W = (1 \text{ m/s})(1 \text{ kg}\cdot\text{m/s}^2)$.

Figure 1

The calibration chain for the HP 8153A optical power meter. This is an example of calibration against a national standard (PTB). In addition, the HP working standards are calibrated at NIST in the U.S.A. Thus the calibrations carried out with these working standards are also traceable to the U.S. national standard. HP also participates in worldwide comparisons of working standards. This provides data about the relation between HP's standards and standards of other laboratories in the world.



Thus, the optical power must be related to mechanical power. Normally such a primary standard is realized by an electrically calibrated radiometer. The principle is sketched in **Figure 2**. The optical power is absorbed (totally, in the ideal case) and heats up a heat sink. Then the optical power is replaced by an applied electrical power that is controlled so that the heat sink remains at the same temperature as with the optical power applied. (The electrical power is related to mechanical units, as shown in the Appendix.) In this case the dissipated electrical power P_{el} is equal to the absorbed optical power P_{opt} and can easily be calculated from the voltage V and the electrical current I :

$$P_{opt} = VI = P_{el}$$

As always, in practice the measurement is much more complicated. Only a few complications are mentioned here; more details can be found in textbooks on radiometry:^{7,8}

- Not all light emitted by the source to be measured is absorbed by the detector (a true black body does not exist on earth).
- The heat transfer from the electrical heater is not the same as from the absorbing surface.
- The lead-in wires for the heaters are electrical resistors and therefore also contribute to heating the sink.

For these and other reasons an accurate measurement requires very careful experimental technique. Therefore,

Figure 2

Principle of an absolute radiometer (electrically calibrated radiometer). The radiant power is measured by generating an equal heat by electrical power. The heat is measured with the thermopile as an accurate temperature sensor. The optical radiation is chopped to allow control for equal heating of the absorber: the electrical heater is on when the optical beam is switched off by the chopper and vice versa.

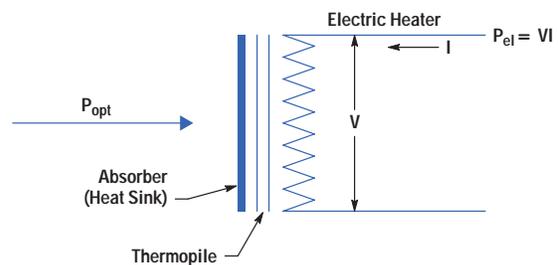
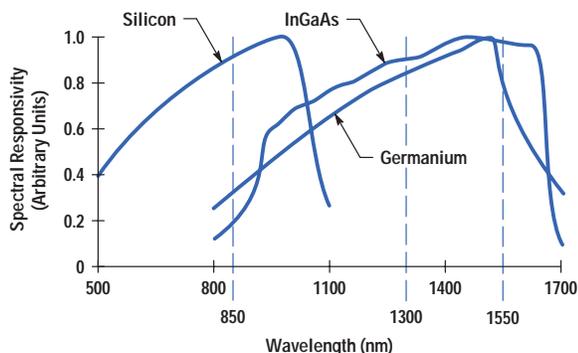


Figure 3

Typical wavelength dependence of common photodiodes.



for dissemination, the optical watt is normally transferred to a secondary standard, such as a thermopile. To keep the transfer uncertainty low it is important that this transfer standard have a very flat wavelength dependence, because the next element in the chain—the photodiode—can also exhibit a strong wavelength dependence (see **Figure 3**).

Normally, absolute power is calibrated at one reference wavelength, and all other wavelengths are characterized

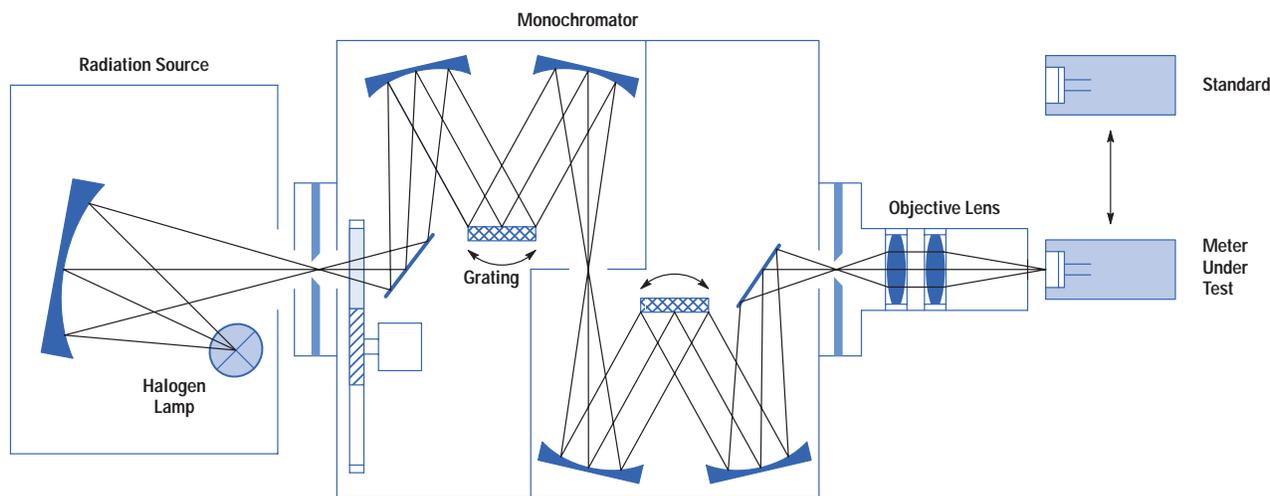
by their relative responsivities, that is, by the dependence of the electrical output signal on the wavelength of an optical input signal at constant power. Because of all the experimental problems related to traceability from optical to electrical (and therefore mechanical) power, an absolute power uncertainty of 1% is hard to achieve. To keep the transfer uncertainties from PTB to the HP calibration lab as low as possible, HP uses an electrically calibrated radiometer as the first device in its internal calibration chain.

For the selection of a certain wavelength, a white light source in combination with a grating-based monochromator is used (see **Figure 4**). This solution has some advantages over a laser-based method:

- A continuous spectrum is available over a very large wavelength range (from UV to the far IR). Lasers emit light only at discrete lines or the tuning range is limited to a few tens of nanometers.
- A tungsten lamp is a classical light source that exhibits almost no coherence effects.
- The power can be kept relatively flat over a large wavelength range.
- The output beam is only weakly polarized.

Figure 4

Calibration setup for absolute power calibration. The monochromator is used to select the wavelength out of the quasicontinuous spectrum of the halogen lamp. The output power as a function of wavelength is first measured with the working standard and then compared with the results of the meter under test. The deviation is used to calculate correction factors that are stored in the nonvolatile memory of the meter.



As always, in practice there are some disadvantages that make a monochromator system an unusual tool:

- A monochromator is an imaging system, that is, external optics are necessary to bring the light into a fiber or onto a large-area detector.
- Available power is rather low compared to the power levels available from telecommunications lasers. Typically 10 μ W is achieved in an open-beam application, but the power level that can be coupled into a fiber may be 30 dB less.
- Because a monochromator is a mechanical tool, a wavelength sweep is rather slow. This can give rise to power stability problems.
- Often the optical conditions during calibration are quite different from the usual DUT's application. This leads to higher uncertainties, which must be determined by an uncertainty analysis.

Thus, setting up a monochromator-based calibration system is not without problems. Nevertheless, for absolute power calibration over a range of wavelengths it is the tool of choice. The calibration is carried out by comparing the reading of the DUT at a certain wavelength with the reading of the working standard at this wavelength. The deviation between the two readings yields a correction factor that is written into the nonvolatile memory of the DUT. In the case of the detectors for the HP 8153A power meter the wavelength is swept in steps of 10 nm over the whole wavelength range. The suitable wavelength range depends on the detector technology. For wavelengths between two calibration points, the correction factor is obtained by appropriate interpolation algorithms. After the absolute power calibration is finished, the instrument can deliver correct power readings at any wavelength.

Calibration of Power Linearity

The procedure described above calibrates only the wavelength axis of the optical power meter. How accurate are power measurements at powers that do not coincide with the power selected for the wavelength calibration? This question is answered by the linearity calibration.

State-of-the-art power meters are capable of measuring powers with a dynamic range as high as 100 dB or more. Ideally, the readings should be accurate at each power level. If one doubles the input power, the reading should also double. A linearity calibration can reveal whether

this is really the case. The linearity of the power meter is directly related to the accuracy of relative power measurements such as loss measurements.

There are several reasons for nonlinearity in photodetectors. At powers higher than about 1 mW, the photodiode itself may become nonlinear because of saturation effects. Nonlinearities at lower powers are normally caused by the electronics that evaluate the diode signal. Internal amplifiers are common sources of nonlinearity; their gains must be adjusted properly to avoid discontinuities when switching between power ranges. Analog-to-digital converters can also be the reason for nonlinearities.

In a well-designed power meter the nonlinearities induced by the electronics are very small. Thus, the nonlinearity of a good instrument is near zero, which makes it quite difficult to measure with a small uncertainty. Indeed, often the measurement uncertainty exceeds the nonlinearity.

The linearity calibration of HP power meters is an example of a self-calibration technique.^{9,10} The nonlinearity NL at a certain power level P_x is defined as:

$$NL = \frac{r_x - r_{ref}}{r_{ref}},$$

where $r = D/P$ is the power meter's response to an optical stimulation, with D being the displayed power and P the incident power. The subscript ref indicates a reference power level, which can be arbitrarily selected. Replacing the responsivity r by D/P , the nonlinearity can be written as:

$$NL = \frac{D_x/P_x}{D_{ref}/P_{ref}} - 1 = \frac{D_x}{D_{ref}} \frac{P_{ref}}{P_x} - 1.$$

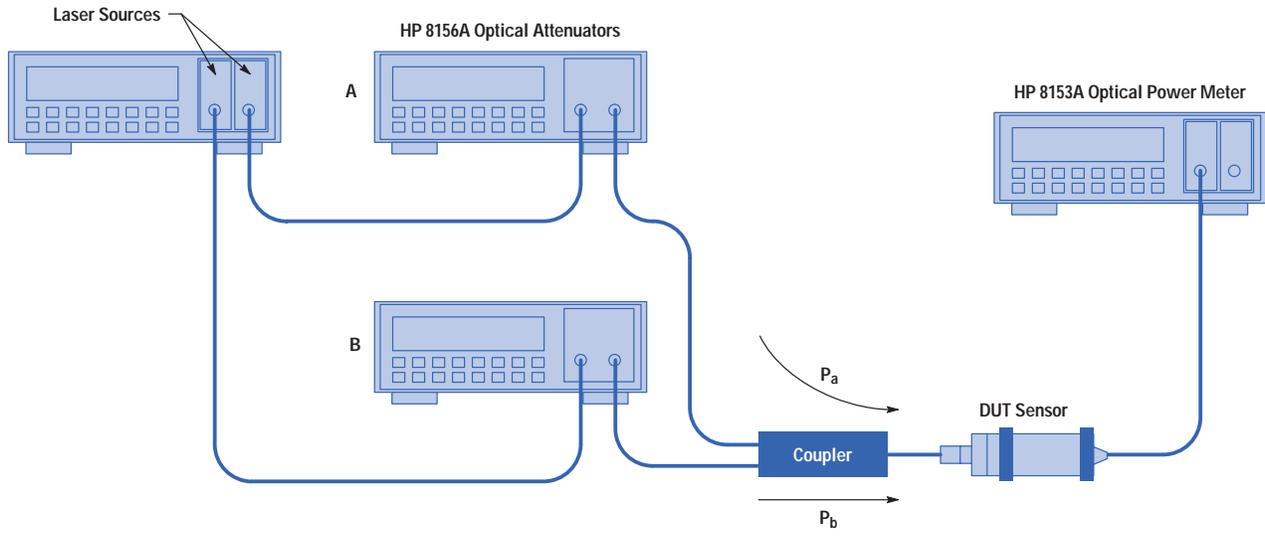
This can now be compared with the error for a loss measurement. Loss means the ratio between two power levels P_1 and P_2 . Let D_1 and D_2 be the corresponding displayed power levels, and define the real loss $RL = P_1/P_2$ and the displayed loss $DL = D_1/D_2$. The loss error LE is given by the relative difference between RL and DL:

$$LE = \frac{DL - RL}{RL} = \frac{DL}{RL} - 1 = \frac{D_1 P_2}{D_2 P_1} - 1.$$

It is evident that if one selects P_1 as reference power, the loss error is given by the nonlinearity at $P_x = P_2$. If P_1 is different from the reference power P_{ref} the statement is still valid to a first-order approximation. The bottom line

Figure 5

Setup for the self-calibrating method of linearity calibration.



is that in relative power measurements like insertion loss or bit error rate tests, linearity is the important property.

The setup for this self-calibration technique is shown in **Figure 5**. First, attenuator A is used to select a certain power P_a , which is guided through optical path A to the power meter under test. The corresponding power reading is recorded. Then attenuator A is closed and the same power as before is selected with attenuator B, resulting in a power reading P_b . Now both attenuators are opened, and the resulting reading P_c should be nearly the sum of P_a and P_b (see **Figure 6**). Any deviation is recorded as nonlinearity. Using the same notation as before, the displayed loss DL is given by:

$$DL = \frac{P_c}{P_a} \approx \frac{P_c}{P_b}$$

The real loss RL can be calculated by adding the two first readings:

$$RL = \frac{P_a + P_b}{P_a} \approx \frac{P_a + P_b}{P_b}$$

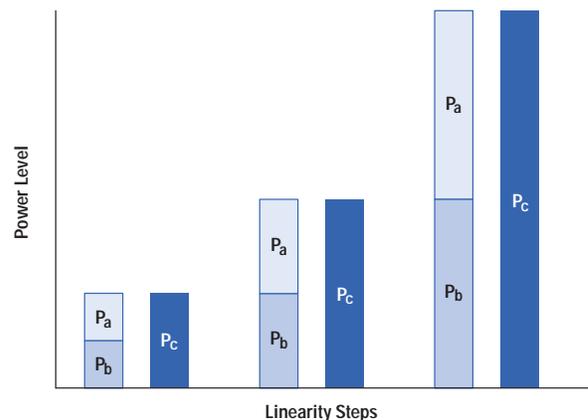
Because P_a and P_b are selected to be equal, the non-linearity NL is:

$$NL = \frac{DL}{RL} = \frac{P_c}{P_a} \frac{P_a}{P_a + P_b}$$

$$\approx \frac{P_c}{P_a} \frac{P_a}{P_a + P_a} = \frac{P_c}{2P_a}$$

Figure 6

The powers selected for the self-calibration procedure. The entire power range is calibrated in 3-dB steps.



The last term on the right side expresses the nonlinearity only in terms of values that are measured by the instrument under test. This means the calibration can be carried out without a standard instrument. Of course, it would also be possible to measure the real loss RL with a standard instrument that was itself calibrated for nonlinearity by a national laboratory. In any case, such a self-calibrating technique has a lot of advantages. There is no standard that must be shipped for recalibration at regular intervals, whose dependencies on external influences and aging contribute to the uncertainty of the calibration process, and that could be damaged, yielding erroneous calibrations.

Calibration of Laser Sources

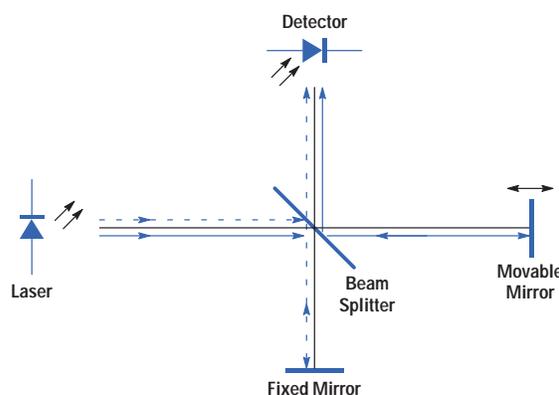
The last example will deal with calibration against natural physical constants and will be used to make some remarks about the determination of uncertainties. Having dealt with optical power sensors we will now focus on sources.

The most commonly used source in optical communications is the semiconductor laser diode. Only a few years ago, the exact wavelength emitted by the lasers was not so important. Three wavelength windows were widely used: around 850 nm, 1300 nm, and 1550 nm. 850 nm was chosen pragmatically; the first available laser diodes emitted at this wavelength. At 1300 nm, fiber pulse broadening is minimal in standard fibers, allowing the highest bandwidth, and at 1550 nm, fiber loss is minimum. As long as a fiber link or network operated at only one wavelength, as was mainly the case in recent years, and all its components exhibited only weak wavelength dependence, the exact wavelength was not of great interest. An accuracy of about 1 nm or even worse was good enough. Indeed, a lot of laser sources are specified with an accuracy of ± 10 nm.

The situation changed completely with the advent of wavelength-division multiplexing (WDM). This means that several different wavelengths (i.e., colors) are transmitted over one link at the same time, allowing an increase in bandwidth without burying new fibers. Since the single channels are separated by only 1.6 or 0.8 nm, one can easily imagine that wavelength accuracy becomes very important. Today wavelength accuracy on the order of a few picometers is required for WDM applications. The task of providing such wavelength accuracy for tunable laser sources like the HP 8168 Series is quite challenging.

Figure 7

Principle of the Michelson interferometer. A coherent beam is split by a beam splitter and directed into two different arms. After reflection at the fixed and movable mirrors, the superposition of the two beams is detected by a photodetector. Because the two beams are coherent, the superposition will give rise to an interference term in the intensity sum. Thus, moving the movable mirror will cause the intensity detected by the detector to exhibit minima and maxima. The distance between two maxima corresponds to a displacement of $\lambda/2$ of the movable mirror, where λ is the wavelength of the laser source. Measuring the necessary displacement to produce, say, ten maxima will allow a direct determination of the wavelength.



The accuracy should be the same over the whole wavelength range. The first question is how wavelength is measured.

First, it should be clear that wavelength means vacuum wavelength, which is effectively the frequency. Unfortunately, the wavelength of light varies under a change of the refractive index of the material it passes through. The tools for measuring nanometer distances are interferometers. Most of the commercially available wavelength meters are based either on the Michelson interferometer or the Fabry-Perot interferometer.¹¹ We will focus on the Michelson technique here.

The principle of the Michelson interferometer is shown in **Figure 7**. The challenge in the case of the Michelson interferometer is to measure the shift of the movable mirror. The required uncertainty of a few pm cannot, of course, be achieved by mechanical means. Instead, the interference pattern produced by light with a known wavelength is compared to the pattern of the unknown

source and by comparison the unknown wavelength can be calculated. The known light source is used here as a natural physical constant. Of course, the wavelength of this source must be independent of external influences. A stabilized He-Ne laser is often used because the central wavelength of its 633-nm transition is well-known and there are several methods of stabilizing the laser wavelength to an accuracy of fractions of 1 pm. Thus, such an interferometer-based wavelength meter is the ideal tool to calibrate a laser source for wavelength accuracy.

As mentioned above, every measurement consists of two parts: the measurement value and the corresponding uncertainty. The uncertainty of a specific measurement is estimated by a detailed uncertainty analysis.¹² As an example, **Table II** shows a fictitious uncertainty calculation for measuring the vacuum wavelength of a laser source with a Michelson interferometer in normal air. As shown, all relevant influences have to be listed and their individual contributions summed. The most difficult part is the

determination of the values of the contributions. For statistical reasons, the sum is gained by a root-sum-square algorithm. This uncertainty calculation is the most important part of a calibration. The quality of the instrument to be calibrated is determined by the results of this analysis. In the case of a calibration process in a production environment, the specifications for all instruments sold depend on it.

In **Table II**, the uncertainty caused by influences from the source under test is considered to be rectangularly distributed. Thus, the standard deviation is $1/\sqrt{3}$ times the uncertainty. In all other cases the standard deviation is known and a Gaussian distribution can be assumed. This leads to an uncertainty of two times the standard deviation at a confidence level of 95%. The Edlén equation is an analytical expression that describes the dependence of the refractive index of air on environmental conditions like temperature and humidity.

Wavelength or Frequency?

Finally, we'll consider the relation between wavelength and frequency. Because the definition of the meter is related to the definition of time and therefore frequency (and moreover, the frequency of light is invariant under all external conditions) it seems that it might be better to measure the frequency of the light emitted by a laser source rather than its wavelength.

It is now possible to measure a frequency of around 100 THz (10^{14} Hz). About two years ago, researchers from PTB succeeded in coupling the frequency of a laser emitting at 657 nm directly to the primary time standard (a Cesium clock as mentioned above) which oscillates at 9 GHz.¹³ This coupled laser is a realization of a vacuum wavelength standard (and therefore a meter standard) which currently has an unequaled uncertainty of 9×10^{-13} .

Unfortunately, this method of directly measuring the frequency of light is very difficult, time-consuming, and expensive, so only a few laboratories in the world are able to carry it out. Thus, for the time being, wavelength will remain the parameter to be calibrated instead of frequency. Nevertheless, this is a good example of how lively the science of metrology is today.

Table II
Example of an Uncertainty Calculation

Component	Standard Deviation ±	Uncertainty ±
Internal Influences:		
Uncertainty of Reference Laser	0.08×10^{-6}	0.15×10^{-6}
Alignment, Diffraction	1.1×10^{-6}	2.2×10^{-6}
Fringe Counting Resolution	0.5×10^{-6}	1.0×10^{-6}
Total 1	1.2×10^{-6}	2.4×10^{-6}
Atmospheric Influences:		
Content of Carbon-dioxide (1/ppm)	0.17×10^{-9}	0.34×10^{-9}
Relative Humidity	1.95×10^{-9}	4.00×10^{-9}
Air Pressure	2.88×10^{-8}	5.76×10^{-8}
Temperature	5.71×10^{-9}	1.14×10^{-8}
Total 2	2.94×10^{-8}	5.88×10^{-8}
Uncertainty of Edlén Equation	1.15×10^{-8}	2.30×10^{-8}
Extension of Wavelength Limits	1.15×10^{-8}	2.30×10^{-8}
Influences from Source Under Test	3.11×10^{-10}	5.38×10^{-10}
Total	1.2×10^{-6}	2.4×10^{-6}

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References

1. W.R. Fuchs, *Bevor die Erde sich bewegte*, Deutsche Verlags Anstalt, 1975
2. W. Trapp, *Kleines Handbuch der Masse, Zahlen, Gewichte und der Zeitrechnung*, Bechternuenz Verlag, Augsburg, 1996.
3. B.W. Petley, *The Fundamental Physical Constants and the Frontier of Measurement*, Adam Hilger, Ltd., 1995.
4. *Calibration of Fiber-Optic Power Meters*, IEC Standard 1315.
5. S. Ghezali, cited by E.O. Göbel, "Quantennormale im SI Einheitensystem," *Physikalische Blätter*; Vol. 53, 1997, p. 217.
6. *Calibration: Philosophy and Practice*, Fluke Corporation, 1994.
7. W. Budde, *Physical Detectors of Optical Radiation*, Academic Press, Inc., 1983.
8. W. Erb, Editor, *Leitfaden der Spektroradiometrie*, Springer Verlag, 1989.
9. C.L. Sanders, "A photocell linearity tester," *Applied Optics*, Vol. 1, 1962, p. 207.
10. K.D. Stock (PTB Braunschweig), "Calibration of fiber optical power meters at PTB," *Proceedings of the International Conference on Optical Radiometry*, London, 1988.

11. *Fiber Optics Handbook*, Hewlett-Packard Company, part no. 5952-9654.

12. *Guide to the Expression of Uncertainty in Measurement*, International Organization for Standardization (ISO), 1993.

13. H. Schnatz, B. Lipphardt, J. Helmcke, F. Riehle, and G. Zinner, "Messung der Frequenz Sichtbarer Strahlung," *Physikalische Blätter*, Vol. 51, 1995, p. 922.

Bibliography

1. D. Derickson, *Fiber Optic Test and Measurement*, Prentice Hall PTR, 1998.



Online Information

Additional information about the HP lightwave products described in this article can be found at:

<http://www.tmo.hp.com/tmo/datasheets/English/HP8153A.html>

<http://www.tmo.hp.com/tmo/datasheets/English/HP8168E.html>

<http://www.tmo.hp.com/tmo/datasheets/English/HP8168F.html>

<http://www.tmo.hp.com/tmo/datasheets/English/HP8156A.html>



Appendix: Realization of Electrical Units

A lot of measurements today are carried out using electrical sensors. Therefore, it is important to know how the electrical units are realized and related to the mechanical quantities in the *Système International d'Unités* (SI). In optical fiber communication all power measurements use electrical sensors.

Historically, the electrical units are represented by the ampere among the seven SI base units. Unfortunately, it is not easy to build an experiment that realizes the definition of the ampere in the SI (see Table I on page 19). It is disseminated using standards for voltage and resistance using Ohm's law. Nevertheless, there is a realization for the ampere (see the current balance in **Figure 1**).

A coil carrying a current I exhibits a force F in the axial direction (z direction) if it is placed in an external inhomogeneous magnetic field H ($F \propto \partial H(z)/\partial z$). The force is measured by compensating the force with an appropriate mass on a balance. The uncertainty of such a realization is around 10^{-6} , the least accurate realization of all SI base units.

A similar principle is used for the realization of the volt, which is not a base but a derived SI unit. For realization one uses the following relation which can be derived from the SI definition of the voltage V (1 volt = 1 watt /ampere):

$$W = V \cdot I \cdot t$$

or

$$V = \frac{W}{I \cdot t}$$

This expression results from the energy W that is stored in a capacitor that carries a electrical charge $I \cdot t$. In this case one measures the force that is necessary to displace one capacitor plate in the direction perpendicular to the plate ($F = \partial W/\partial z$). Again the accuracy is about 10^{-6} . The approximate uncertainties in realization and representation of some SI units are listed in **Table I**.

Table I

Uncertainty of realization and representation of selected units of the SI system. Note that the representation of the voltage unit has a lower uncertainty than its realization.

Unit	Uncertainty of Realization	Uncertainty of Representation
kilogram	0	8×10^{-9}
meter	9×10^{-13}	3×10^{-11}
second	1×10^{-14}	1×10^{-14}
volt	1×10^{-7}	5×10^{-10}

However, in contrast to the ampere, for the volt there is a highly accurate method of representing the unit: the Josephson effect. The Josephson effect is a macroscopic quantum effect and can be fully understood only in terms of quantum physics. Only a brief description will be given here.

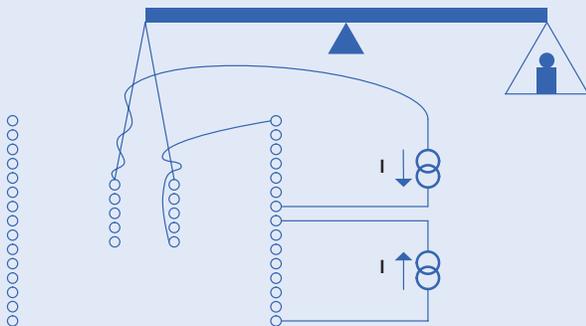
A Josephson element consists of two superconducting contacts that are separated by a small insulator. Astonishingly, there is an electrical dc current through this junction without any voltage drop across the junction. This is the dc Josephson effect. If one now applies an additional dc voltage at the junction, one observes an additional ac current with a frequency f that depends only on the applied dc voltage V and the fundamental constants e (charge of the electron) and h (Planck's constant):

$$f = \frac{2eV}{h}$$

This effect can be used to reproduce a dc voltage with very high accuracy. One applies a dc voltage V and a microwave frequency f at the junction and observes a superconducting mixed current with ac and dc components. For certain voltages, and only for these

Figure 1

Principle of a current balance. The force experienced by the inner coil is compensated by an appropriate mass on the balance.



voltages, there is a resulting dc current in the time average. The condition is:

$$V = nf \frac{h}{2e}, \quad n = 0, 1, 2, \dots$$

The uncertainty in reproducing a certain voltage V thus depends only on the uncertainty of f . As shown above, time and therefore frequency can be reproduced very accurately. One only has to control the microwave oscillator with a Cesium time standard. With

this setup, an accuracy of 5×10^{-10} is achievable in the representation of the voltage unit, which is about 10,000 times better than the accuracy in realization—really a strange situation.

One solution would be to fix the value for e/h , similar to what was done for the new definition of the meter by holding the value for c constant. It would then be possible to replace the ampere as an SI base unit by the volt and define the volt using the Josephson effect.

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