Procedure Title: **Laser Frequency Calibration**
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References

1. T.J. Quinn, "Practical realization of the definition of the metre [1997]", Metrologia **36**, 1999, p.211-244.

Introduction

Note that the iodine-stabilized laser can achieve an expanded (k=2) uncertainty as small as 24 kHz[1] (5×10^{-11}relative uncertainty), much better than is required to calibrate the frequency/vacuum wavelength of other types of commercial stabilized lasers. The uncertainty of a calibration is limited by the stability of the laser under test to a value typically above 500kHz and almost never below 100 kHz. The quantitative requirements of process control appropriate for establishing these levels of uncertainty will vary depending on the stability of the laser under test.

The two most likely cause of serious error (>100kHz) in a laser frequency/wavelength calibration are: (a) locking to the wrong iodine line and (b) miscounting by the frequency counter due to low signal strength or the presence of spurious signals. It is of great importance to institute a check standard that provides process control to ensure that these sources of error are small.

When commercial stabilized lasers are calibrated, an appropriate check standard is provided by one of the well-known frequency differences between two absorption lines of iodine. A check is carried out by repeatedly alternating between two iodine lines while measuring the beat frequency between the iodine-stabilized laser and the test laser. The two lines should be chosen so that the two beat frequencies with the test laser differ from each other by as much as practical, certainly by more than 10%. The computer program that controls laser calibrations automatically does the following: Switch back and fourth ten or more times between two iodine lines (denoted in the following discussion by subscripts "1" and "2"), stopping on each line to measure the beat frequency. Find the average beat frequencies f_{b1} and f_{b2} for the lines and for each of these averages compute the two standard deviations of the mean s_{b1} and s_{b2}. Define a parameter $U = 2\times\mathrm{sqrt}(s_{b1}^2+s_{b2}^2)$, an estimate of the expanded (k=2) uncertainty of the measurement of $f_{b1}\pm f_{b2}$. Depending on the frequency of the test laser relative to the two iodine lines, either the sum or the difference of the two beat frequencies $|f_{b1}\pm f_{b2}|$ should be equal to the known line spacing $|f_1-f_2|$. The computer determines whether sum or difference is appropriate and finds the deviation δf of $|f_{b1}\pm f_{b2}|$ from $|f_1-f_2|$.

Check Standard: The line spacings of the set of iodine lines d, e, f, g, h, i, j can be used as check standards to assure that the measurement is correct. The spacings are given in the Mise en Pratique[1] with an expanded uncertainty of 10 kHz, and we take this value as a limit that should not be exceeded; δf should be less than 10 kHz *if the laser under test is sufficiently stable to measure δf with a suitably low uncertainty* (usually not the case). In many cases the stability of the laser under test is not sufficiently good for us to determine the line spacing with this accuracy (and under these circumstances there is no need to test results so stringently since the test laser frequency fluctuations will require a large uncertainty in the reported result). The criterion adopted here for a measurement to be in control is that δf should not exceed 10 kHz within the uncertainty band imposed by laser frequency fluctuations. More precisely,

If $\delta f<[U^2+(10\ \mathrm{kHz})^2]^{1/2}$, then the measurement passes the test and is considered to be in control.

An additional requirement would be useful—to demand that U is not unusually large, but this requirement is difficult to implement in a statistically sound manner because U can vary by more than an order of magnitude depending on the model of stabilized laser under test. It is our experience that for most commercial stabilized lasers U< 1 MHz. If U exceeds 1 MHz, or if U is significantly larger than has been seen in the past for stabilized lasers of the same brand, then it is prudent to take additional steps to ensure that the large fluctuations do not reflect the presence of electrical noise or are a consequence of optical feedback. The optical set-up should be examined to ensure that feedback is not present. The beat between the laser under test and any stabilized laser known to have sufficiently small short-term frequency fluctuations can be observed on a RF spectrum analyzer to determine if the laser under test is indeed subject to megahertz-level fluctuations. (Measurement by an RF spectrum analyzer provides an independent check that essentially eliminates errors from electrical noise and miscounting in the frequency counter).

The test above ensures both that that (a) the iodine-stabilized laser is locking to the correct lines without any catastrophic failures and (b) frequency measurement is not subject to large enough errors that it will alter results at a level of consequence for most of our calibrations. However, this process control is not sufficiently rigorous to ensure the validity of results under the stringent circumstances described in the next section.

Special situations requiring additional checks:

Usually we calibrate lasers with a quoted uncertainty greater than 200 kHz, and under these circumstances the process control described above is sufficient to ensure that the uncertainty of a measurement will be as claimed; it is unlikely that any failure mode of either the frequency measurement or the iodine-stabilized laser could cause 200 kHz errors while still passing the test described above. However, if the stability of the laser under test is sufficient to achieve an expanded uncertainty of less than 200 kHz (4×10^{-10} relative expanded uncertainty) then additional tests will be required to ensure that the measurement is correct.

One straightforward method for verifying the claimed uncertainty is to determine the test laser frequency using two independent systems— two iodine-stabilized lasers and two frequency counters. We can expect that the two iodine stabilized lasers should have the same frequency within a maximum range of about 50 kHz, even if one or both lasers is badly out of adjustment, and this range can normally be reduced below 24 kHz when the operating parameters of both lasers have been optimized. For two optimized lasers, the absolute maximum expected difference would be $24\ \text{kHz}\times2^{1/2}$=33kHz. We therefore require that the difference in the averaged frequency measurements with the two systems, f_1-f_2, should not exceed 33 kHz within the uncertainty band imposed by fluctuations in f_1 and f_2 due to variations in the test laser frequency: $|f_1-f_2|< [\ (2\sigma_1)^2+(2\sigma_2)^2+(33\text{kHz})^2]^{1/2}$.

In the rare case when a customer might send an iodine stabilized laser for calibration and need the ultimate 24 kHz uncertainty for frequency measurement, additional testing by an expert will be required.

An alternative is to periodically check the operation of the frequency counter and to periodically compare the iodine-stabilized laser to a second iodine-stabilized laser. This laser comparison should be carried out at least once every two years, and the lasers should demonstrate agreement within 33kHz as expected based on the combined uncertainties of the two iodine-stabilized lasers [24 kHz×sqrt(2)].

Finally, note that at these very highest levels of accuracy all operations should be carried out by an expert familiar with the required adjustments of the iodine stabilized laser.

Calibration History: When lasers are sent for recalibration, measurements should be compared to previous measurements. When the current result does not agree with history within the expanded uncertainty, the discrepancy should be brought to the attention of an expert who may, at his discretion, order additional investigations to ensure that the measurements were performed correctly. Similarly, any other unusual behavior observed during the calibration of a laser should be brought to the attention of an expert.