Using un-calibrated lasers as wavelength standards

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National Institute of Standards and Technology

Customers ask:

Q: Is the He-Ne laser wavelength an intrinsic atomic property that does not need calibration in order to be traceable to the SI unit?

A: Yes!

Q:My length measurements only need an uncertainty of 3 parts in 10^6; do I need to send my laser to you for calibration?

A: No!

Authority for these answers:

Working Group on Unstabilized Lasers of the Consultative Committee for Length (CCL):*J. A. Stone, J. E. Decker, P. Gill, P. Juncar, A. Lewis, G. D. Rovera, M. Viliesid*

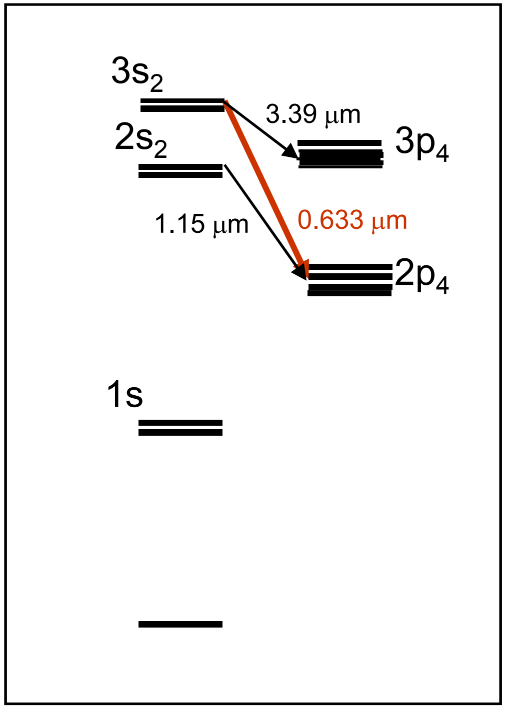
2007:CCL recommended that unstabilized and/or uncalibrated helium-neon lasers operating at 633 nm should be included in the list of standard frequencies

This ends the short version of my talk!

…. but we probably need to consider this in a little more detail! There are caveats and subtleties that need to be discussed.

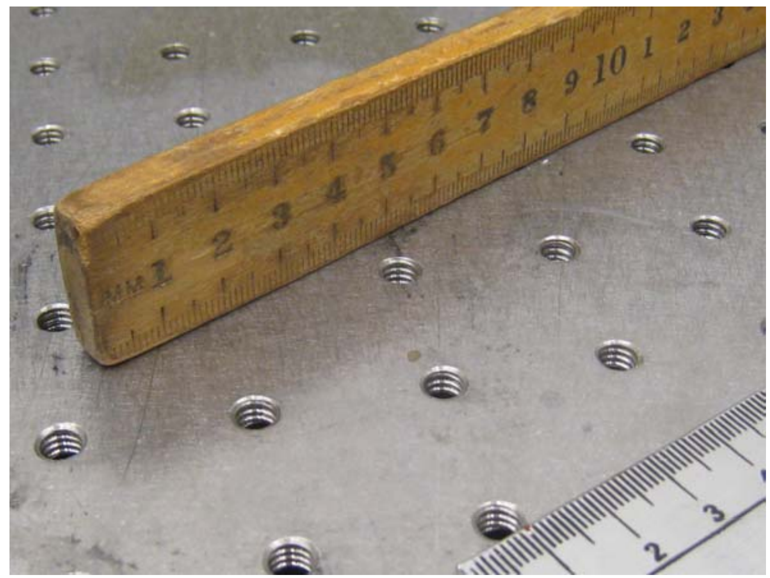
Remember: in spite of such caveats, the fundamental conclusions have already been given and will not change.

Can you use a wavelength standard without calibration?



Red transition of the common He-Ne laser: fixed by atomic properties of the neon atom

.... Or is it just another meter stick ?



What the physics tells us:

The red helium-neon laser, operating on the $3s_2 \rightarrow 2p_4$ transition, has a wavelength λ= 632.9908 nm (in vacuum)

Possible deviations from this value by individual lasers will not exceed 3 parts in 10^6 (estimated k=2 uncertainty)

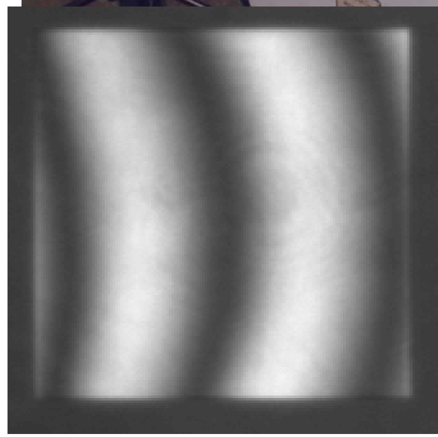
For many applications, this uncertainty is very satisfactory. When a laser is used for these applications, an auditor ***should not*** demand that it be calibrated.

Displacement-measuring laser interferometers often need only modest fractional uncertainty:

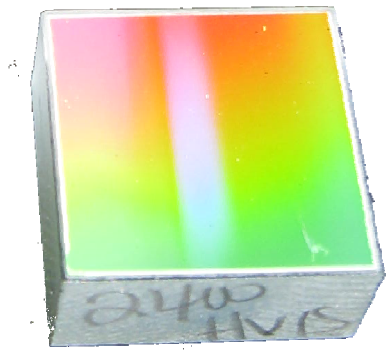
-- short distance measurements

--low accuracy check of a machine motion

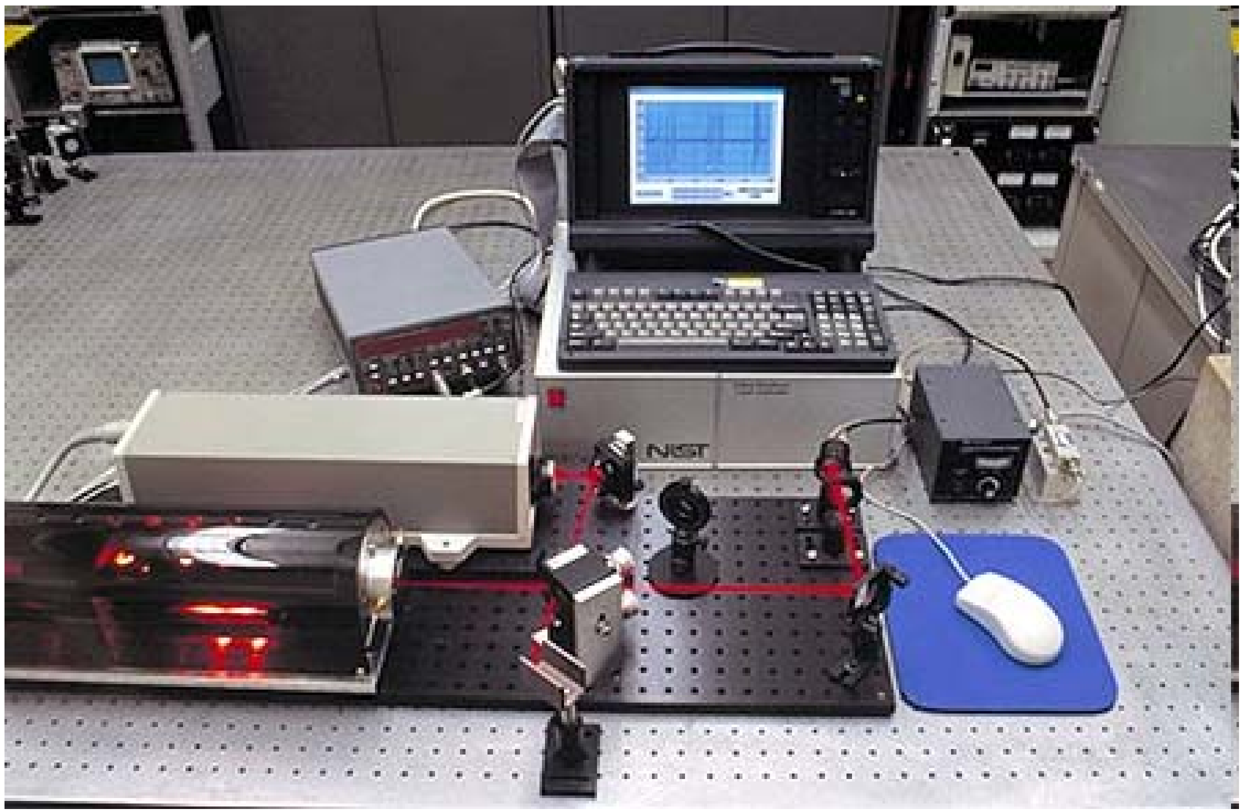
Fizeau interferometry: with less than 10 fringes across the field of view, accuracy of 1 part in 10^4 = 0.3 nm. (often employs unstabilized laser)



Grating pitch calibrations require relative uncertainties ranging from 10^{-3} to 10^{-5} (often employs unstabilized laser)



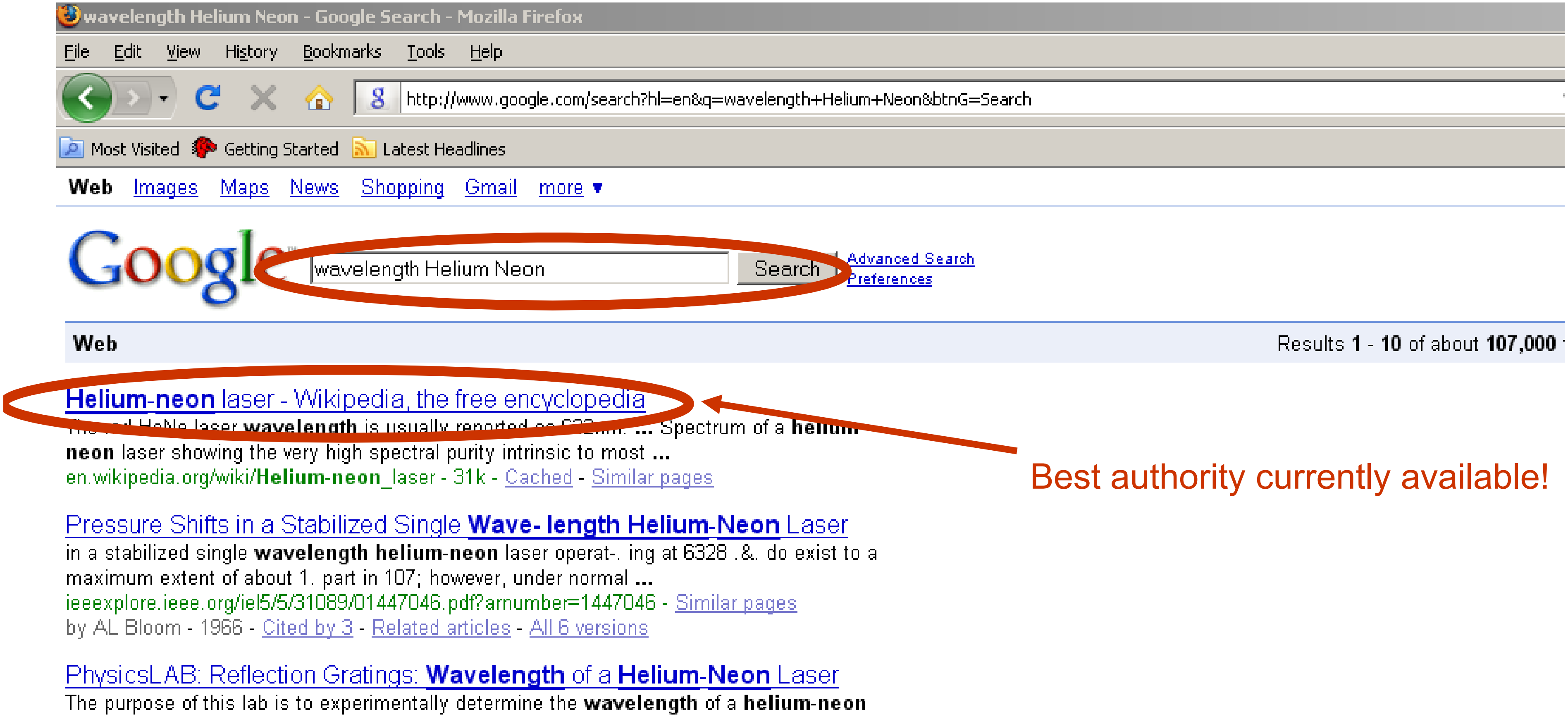
For these low-accuracy applications, why are we doing heterodyne calibrations of frequency/wavelength?



How might you convince your auditor that you know the wavelength without calibration?

--need an authority.

Find an authority….



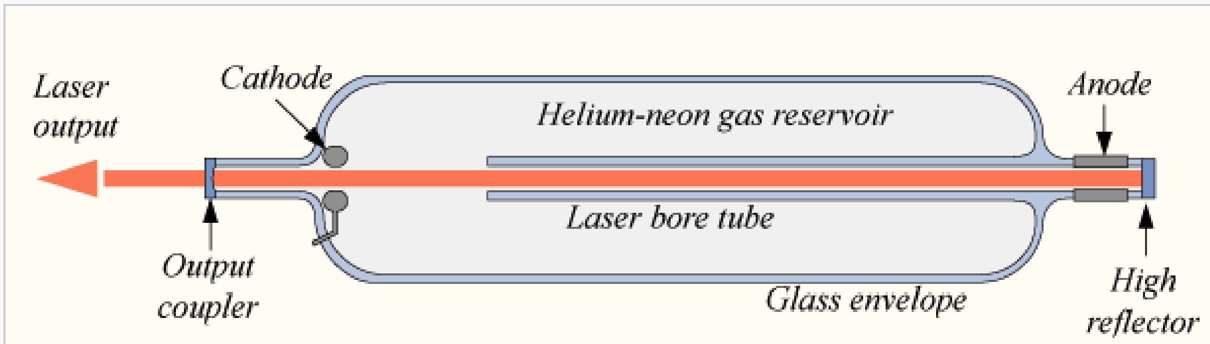
Best authority currently available!

….now convince your auditor that Wikipedia is authoritative???

Helium-neon laser

From Wikipedia, the free encyclopedia

A **helium-neon laser**, usually called a **HeNe laser**, is a type of small gas laser. HeNe lasers have many industrial and scientific uses, and are often used in laboratory demonstrations of optics. Its usual operation wavelength is 632.8 nm, in the red portion of the visible spectrum.[1]



Schematic diagram of a helium-neon laser

The gain medium of the laser, as suggested by its name, is a mixture of helium and neon gases, in a 5:1 to 20:1 ratio, contained at low pressure (an average 50 Pa per cm of cavity length [2]) in a glass envelope. The energy or pump source of the laser is provided by an electrical discharge of around 1000 volts[citation needed] through an anode and cathode at each end of the glass tube. A current of 5 to 100 mA is typical for CW operation.[3]. The optical cavity of the laser typically consists of a plane, high-reflecting mirror at one end of the laser tube, and a concave output coupler mirror of approximately 1% transmission at the other end.

HeNe lasers are typically small, with cavity lengths of around 15 cm up to 0.5 m, and optical output powers ranging from 1 mW to 100 mW.

The red HeNe laser wavelength is usually reported as 632nm. However, the true wavelength in air is 632.816 nm, so 633nm is actually closer to the true value. For the purposes of calculating the photon energy, the vacuum wavelength of 632.991 nm should be used. The precise operating wavelength lies within about 0.002 nm of this value, and fluctuates within this range due to thermal expansion of the cavity. Frequency stabilized versions enable the wavelength to be maintained within about 2 parts in 10^{12}[4] for months and years of continuous operation.

UNITED STATES DEPARTMENT OF COMMERCE
National Bureau of Standards
Washington, D.C. 20234

October 18, 1976

Dear Mr. :

The question you raise concerning the traceability to national standards of interferometers utilizing the 0.633 μm line of the He-Ne laser is one that we have faced before. It is our opinion

Better authority: Letter from an NMI:

"The physical principles of laser action preclude any He-Ne laser from producing light of a wavelength that differs from the accepted value…by more than 1 part in 10^6."

…. This is still not a good solution.

laser interferometers and considers all such devices traceable to national standards in all the usual contexts.

Sincerely,

s/JAS

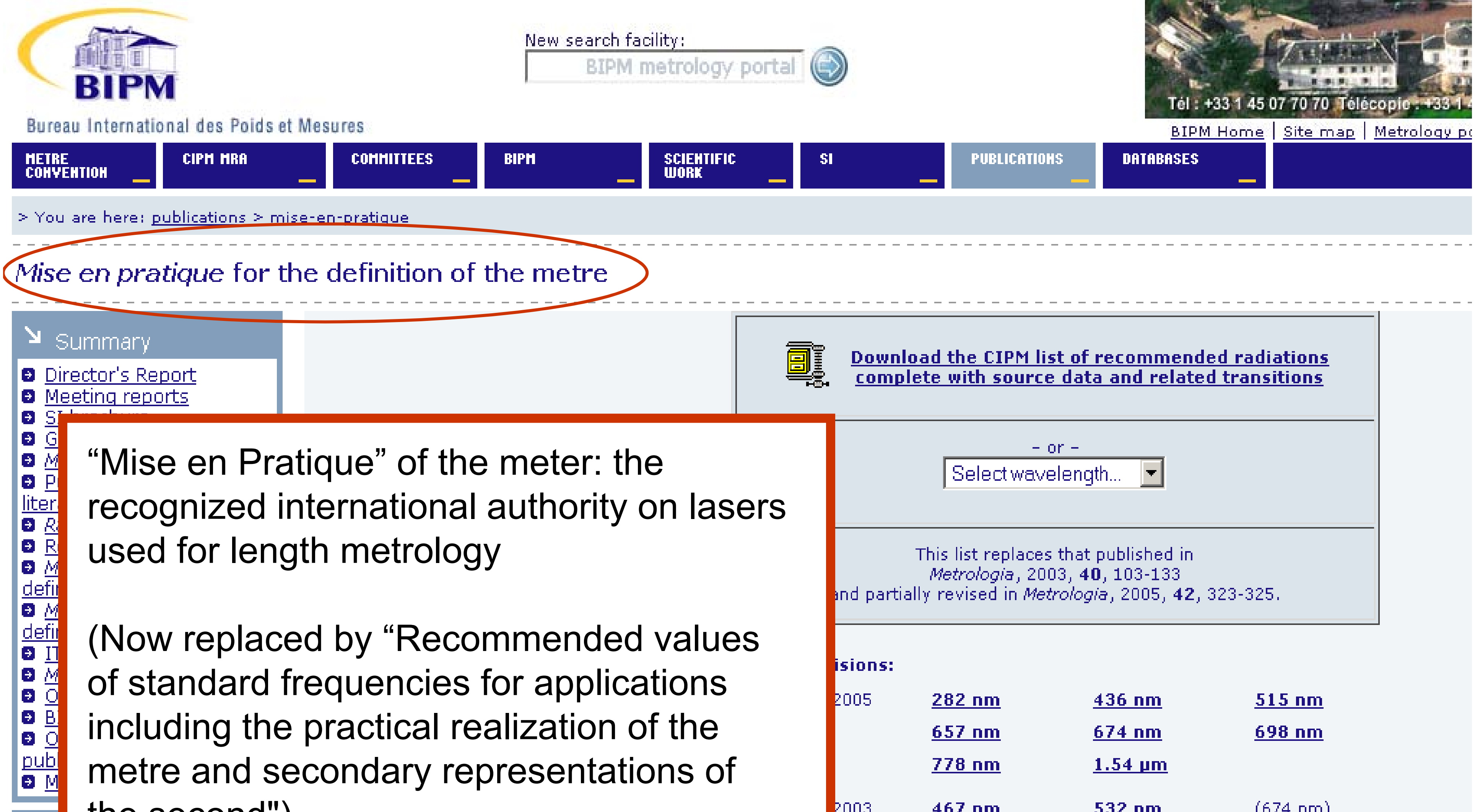
John A. Simpson
Acting Chief
Mechanics Division

10/18/76.

75 YEARS NBS

Best Authority: Standards

- Develop ISO or B89 standards
- This is indeed what is needed. And we have not yet started this process.
- Groundwork: first establish international consensus regarding technical issues



"Mise en Pratique" of the meter: the recognized international authority on lasers used for length metrology

(Now replaced by "Recommended values of standard frequencies for applications including the practical realization of the metre and secondary representations of the second")

CCL working group was formed to study the issue of unstabilized lasers:

Working Group on Unstabilized Lasers of the Consultative Committee for Length: *J. A. Stone, J. E. Decker, P. Gill, P. Juncar, A. Lewis, G. D. Rovera, M. Viliesid*

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A forthcoming article in Metrologia will summarize the findings of the Working Group.

Issues

- Is the uncertainty “too big” to be in a list of recommended radiations?
- Will this invite endless new entries in the List of Standard Frequencies (MeP)?
- What to assign for wavelength and uncertainty.
- What to do about the possibility of 640 nm radiation.

Is the uncertainty “too big” to be in a list of recommended radiations?

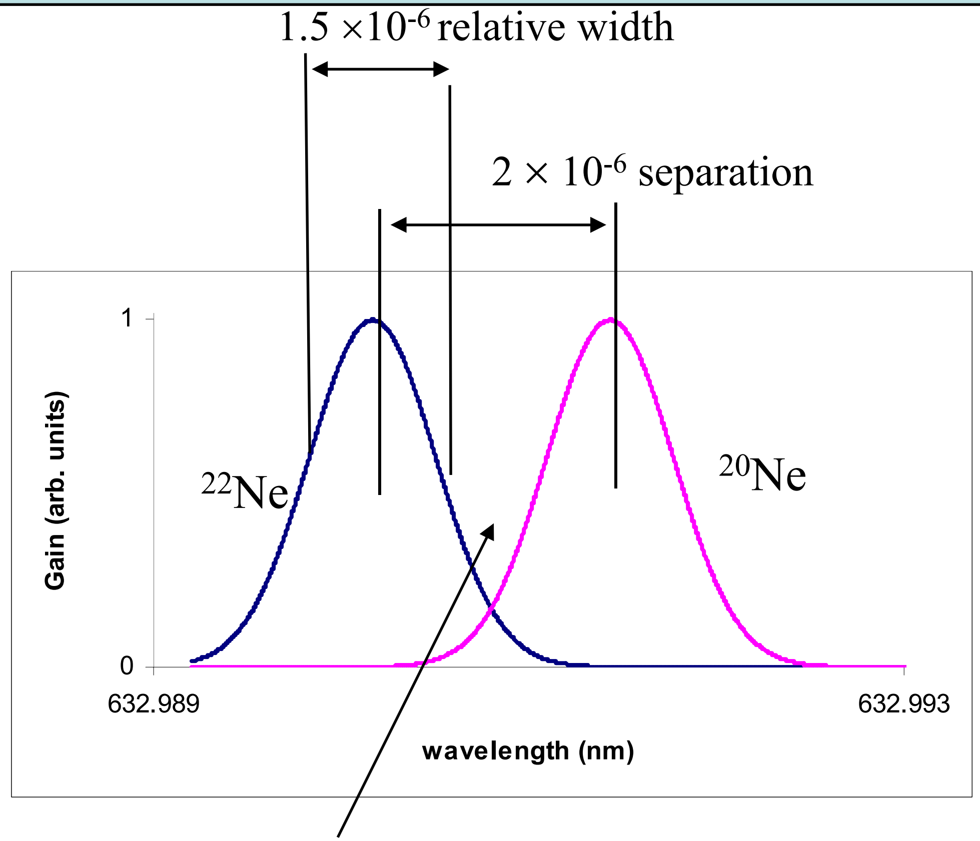
Some frequency/wavelength standards

Comb-generated	$\approx 10^{-16}$ (limited by Cs clock)
Iodine stabilized laser:	$\approx 10^{-11}$
Spectral lamps	$\approx 10^{-8}$
Uncalibrated laser	$\approx 10^{-6}$

Set out criteria to avoid undesirable entries

- Is the standard based on well known atomic or molecular properties of a substance that are not likely to be perturbed at the claimed uncertainty level?
- Can the standard be realized in practice with a widely available embodiment?
- Do we have enough experience with available embodiments of the system to understand potential pitfalls and how these pitfalls can be avoided?
- Is there a clear need for a standard that may not be of the best uncertainty but is generally available in a trustworthy form?
- Does inclusion of the standard in a recommended list provide a clear overall benefit to length metrology?

Value and Uncertainty



- Assigned value half way between two isotopes.

- Uncertainty is primarily due to isotope shift and Doppler width of gain profile.

The problem of 640 nm radiation

- Some lasers, designed to operate at 633nm ($3s_2 \rightarrow 2p_4$ transition), may have a small amount of contamination at 640 nm ($3s_2 \rightarrow 2p_2$).
- Historically, this was a significant problem…

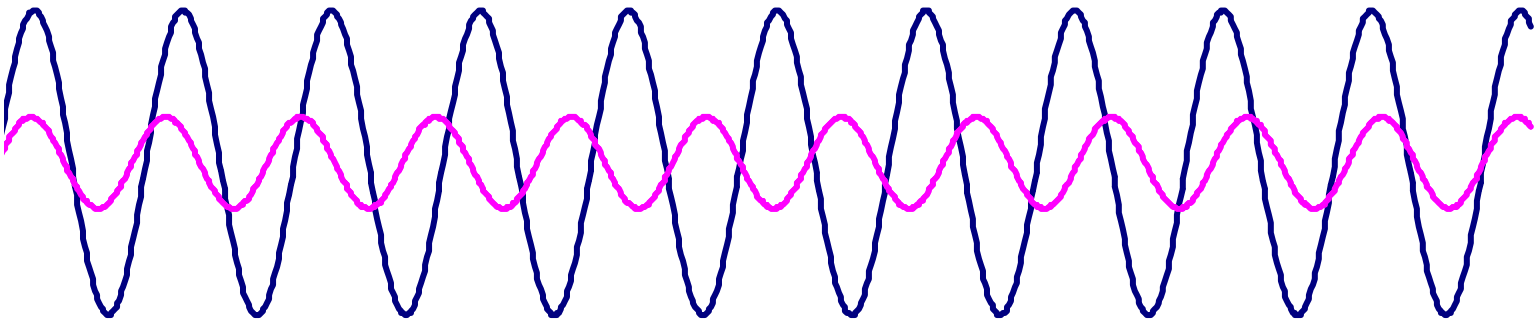
Nature of the problem now:

•For short lasers: no evidence of trouble among those currently in production.

•For long, high-power lasers: Most likely, a few percent exhibit problems.

•Among remaining lasers: 640 nm contamination may typically constitute a few percent of total output power--small enough that it does not affect most users.

Errors in interferometry



Small contamination (pink) at a different wavelength shifts phase of interference in a manner that varies periodically in space as the waves go in and out of phase.

Errors in interferometry almost negligible.

•For interferometry: no length-proportional error, but 640 will perturb the phase in a manner that repeats with the synthetic wavelength.

•4% contamination will shift fringe $\leq \pm 2$ nm. For measurement range in excess of 45 fringes, could have an error as large as 4 nm.

For state-of-art Fizeau interferometry, could be non-negligible, but error is ≤ 0.27 nm with only 2 fringes across surface, as would be typical for highest-accuracy measurements.

Another example: grating pitch

4% spurious radiation at 640 nm could shift the measurement results by 4 parts in 10^4.

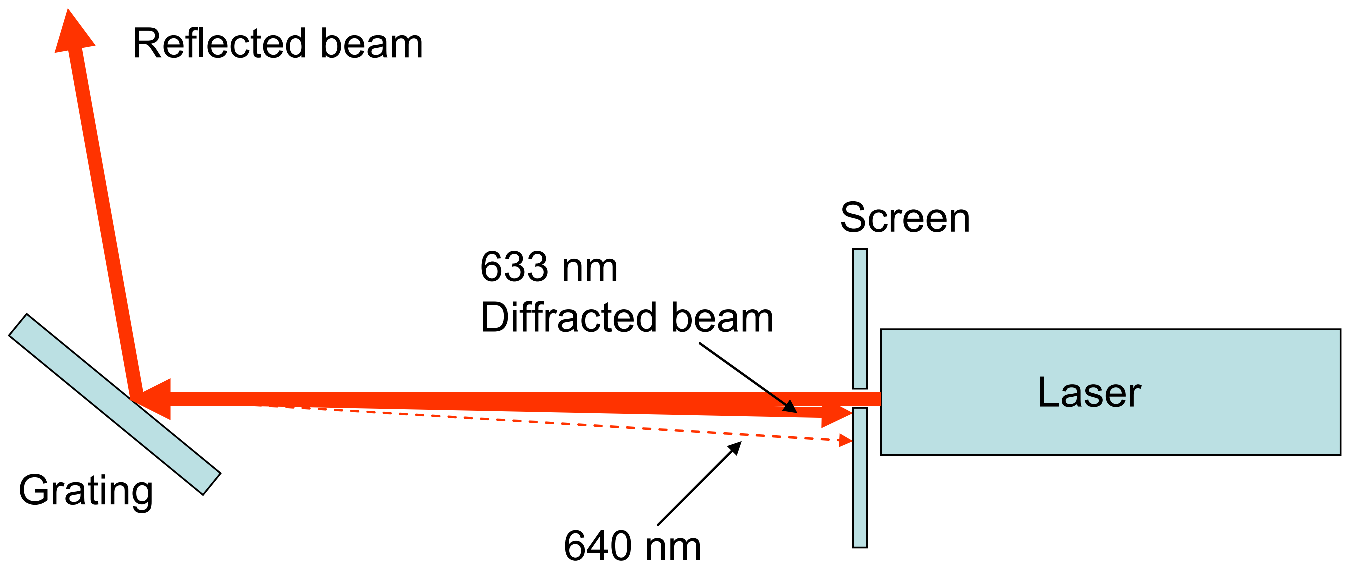
However, in high-resolution measurements, it is likely that the 640 nm peak would be rejected in software or hardware, and thus would have no effect at all.

Warnings

In some cases, additional testing could be called for. But in the words of the subcommittee:

"Particularly in the case of short lasers, it would be unproductive to carefully test for a problem when there is no evidence that it occurs in practice. Furthermore, as will be shown in the examples below, for most applications the potential impact of 640 nm radiation on the measurement is quite small. Whereas it might be prudent to test for 640 nm radiation when sub-nanometer uncertainty is required of a length-measuring interferometer, the benefit is dubious for more typical applications, such as when using an interferometer that has only 10 nm resolution."

Simple test can be done by almost anyone: no need to send laser to testing lab or NMI



Conclusion regarding 640 nm:

There is a potential for measurable errors, but it is not **clear** that 640 nm is causing significant errors in ***any existing application***.

Need to balance the fact that error is possible against the extremely small probability of such an error occurring.

One possibility: encourage interlaboratory comparisons or performance testing: check overall measurement process so that there is a greater chance of getting some benefit from the test.

Overall Conclusions

•The vacuum wavelength of typical red He-Ne lasers, operating solely on the $3s_2 \rightarrow 2p_4$ transition, is a reliable atomic standard of wavelength, with a relative standard uncertainty of 1.5×10^{-6}.

•For applications where the uncertainty is acceptable, *no* value in heterodyne calibration: no reason to require it.

• The uncertainty above is only one component of an overall measurement uncertainty budget: note particularly, that wavelength in air may have higher uncertainty.

(Again, interlaboratory comparisons of measurement results may be helpful to establish confidence)