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Frequency and Wavelength Standards, Present and in Prospect [and Discussion]

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Frequency and wavelength standards, present and in prospect

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Techniques have now been developed that allow direct measurement of frequencies through the infrared and into the visible. They have already yielded spectroscopic standards more precisely known through their frequencies than their wavelengths and have made it attractive to redefine the international metre in terms of the speed of light and the primary time standard. The implications for spectroscopy of these techniques and of improved methods for wavelength comparison are discussed.

Wavelength standards

The differences in energy states in atoms and molecules, the essential quantities used in spectroscopy, are manifest as frequencies of radiations emitted or absorbed as a result of transitions between the states. Since the frequencies of optical radiations were far too high to be measured directly, spectroscopists have measured wavelengths, the reciprocal of which, the 'wavenumbers', gave $1/c$ times the frequency. Measurement of relative values of wavelengths has been straightforward, usually by the use of optical devices to provide a common length retardation to part of the beam so that wave interference resulted in an output angle or intensity variation related in a simple way to the wavelength. The common retardation was provided by separation of interferometer reflectors, adjacent grooves of a grating, etc. The role of the common physical length in these measurements is significant and can lead to results different from a true frequency comparison because of dispersion in various effects such as the phase change on reflexion. Thus they are properly designated length comparisons even though, as in some modern comparison techniques, frequency methods are used in interpolating between the cyclical intensity changes produced by interference.

In general, it was only differences in wavenumber values that were necessary to set up a highly accurate, consistent theory. A much less accurate value for c, the speed of light, was used only to tie the data in with other physical measurements; c was known from other types of measurements. The wavenumber values needed only to be known relative to that of an accurately reproducible standard radiation. It was possible, nevertheless, by the use of interferometers, to relate very accurately the optical length to physical lengths, leading to the definition of the international metre in 1960 in terms of the 0.606 μm radiation of ^{86}Kr. Between 1907 and 1961 wavelengths were usually expressed in terms of the spectroscopists own length unit, the ångström, which was defined in terms of the red line of cadmium so as to be as close as possible to 10^{-10} m. In 1961 the ångström was redefined as exactly 10^{-10} m. The history of these developments has been summarized by Edlén (1963) and Terrien (1976).

With the development of modern spectroscopy the range of wavelengths whose values have been required has been extended to cover a range from picometres to centimetres involving a wide variety of techniques, instruments and detectors of which no single combination could be used to cover a very large part. Spectroscopists established, in addition to a primary standard,

an extensive set of secondary standards to provide a common 'absolute' scale over the whole spectrum. This was the result of contributions of a great many individual efforts as well as from national laboratories, notably the U.S. National Bureau of Standards, and it has benefited from coordination by international organizations such as the International Astronomical Union, the Inter-Union Commission of Spectroscopy of ICSU and the International Committee of Weights and Measures (CIPM). These organizations report the continual updating and extension of the system of wavelength standards.

The accuracy to which wavelengths can be compared depends on the nature of the radiation and the comparison technique. The radiation emitted by suitably controlled single isotope thermal sources such as the ^{86}Kr primary standard line have a width only about $10^{-6}\lambda$ and suffer perturbations of the order of 1% of the width; the latter are known to about 10% of their magnitude so that such sources produce radiation reproducible to about $10^{-9}\lambda$. There are a number of such lines in the visible and near i.r. part of the spectrum that serve as the best secondary standards and their wavelength values are listed by the CIPM. On the other hand, other lines such as some in the iron spectrum are not significant to much better than $10^{-5}\lambda$ because of asymmetry, overlapping lines, dependence on source conditions, etc. Comparison techniques range from the convenient use of angular dispersion, as given by grating spectrometers, to the much more accurate methods using interferometry. The setting sensitivity of comparison techniques has gradually been improved since the early days of visually setting cross-wires on spectral lines or interference fringes, by the use of photoelectric scanning techniques developed in the 1950s. These yield, without much trouble, better than 10^{-3} of the line width, making possible the studies necessary to establish the accurate standards mentioned above. Apart from errors of setting, serious systematic errors can arise from a number of pitfalls, as described in standard texts, largely resulting from failure to realize commonality of the lengths that are effective for the different radiations being compared. These factors, together with difficulties associated with different wavelength regions (e.g. the large diffraction corrections at long wavelengths, difficulties with optical materials at very short wavelengths, and the effect of source parameters in the X-ray region) have resulted in considerable variation in the accuracy of standards and measurement across the spectrum; the most accurate traditional type standards being those in the visible mentioned above. A recent summary of the whole gamut of wavelength standards has been given by Baird (1979).

The advent of the laser led to a new set of standards markedly superior to the above, not because emissions of lasers themselves are precise but because it is possible to servo-control the very narrow laser radiation so as to be centred on sharp, unperturbed absorption lines by the use of techniques to eliminate Doppler broadening (see Brillet & Cerez 1981). This has resulted in reference standards 10^3 to 10^5 times narrower and less subject to perturbation than thermal sources; a number of them, together with recommended wavelengths, have been listed by the CIPM, such as certain lines in the spectrum of CH_4, and I_2. Such sources would allow the adoption of a primary standard orders of magnitude better than the present international metre. However, the coherence of these sources and the concomitant development of high-speed nonlinear optical devices have offered a much more attractive alternative.

It is now possible to extend the accurate measurement of frequency to the region of the spectrum where wavelengths can be accurately measured. As a result there has been an 'orders of magnitude' increase in the accuracy of the knowledge of the speed of light through the relation $c = f\lambda$. Not only does this hold the promise that spectroscopists can directly

measure the *frequencies* of radiations, their real interest, but also that the metre can be redefined so as to be based on the same standard as that used for time, with the adoption by convention of an exact value for the speed of light. Steps now being taken by international committees aim at the adoption of such a definition at the Conférence Générale des Poids et Mesures in 1983. It will probably be of the form 'the metre is the distance travelled by light in vacuum during the fraction 1/299 792 458 of a second'. The most precise wavelengths would then be derived from measurements of frequencies and the adopted value of the speed of light, 299 792 458.

Measurement of optical frequencies

Frequencies of electromagnetic oscillations up to about 500 MHz can be counted directly electronically, but the measurement of higher frequencies requires the use of harmonic generation and heterodyning techniques. The principle is as follows: a device that has a nonlinear response will convert a sinusoidal signal into an output that is distorted, i.e. it contains harmonics of the original signal. Similarly, such a device will convert a mixture of two sinusoidal signals of slightly different frequencies into an output that contains a signal corresponding to the difference in the frequencies or 'beat' between the two original signals. A count of the beats over a period of time yields *exactly* the difference in the number of cycles of the original signals. It can be seen that if two signals, one of which is nearly equal to a harmonic of the other, are impressed upon such a device having a suitable nonlinear response, the rather complicated output will contain a low frequency signal of frequency equal to the difference between the one and the harmonic of the other. A measurement of the frequency of the beat, f_b, will yield the value of the higher frequency f_h in terms of the lower f_l, $f_h = Nf_l + f_b$. Thus even very high frequencies can be measured provided the beat is low enough to handle in convenient electric circuits and to be measured and counted. The only requirement for very high-speed response is in the device for harmonic generation and mixing. Of course it is important that the oscillations are sufficiently coherent (i.e. they must suffer frequency changes sufficiently slowly) to allow the observation of enough beat oscillations to make a significant measurement. When suitably applied, the method makes it possible to measure the number of oscillations of the higher frequency signal during a given number of periods of the lower, *without missing one*. Alternatively the beat signal can be used to servo-lock one of the frequencies to the other for an indefinite time, to within one cycle.

Two major developments have made it possible to apply the above principle to extend frequency measurement to the optical region of the spectrum: the first was the invention of the laser, which satisfied the coherence requirement, and, with the associated development of Doppler-free spectroscopy and techniques for stabilization, provided very precise reference standards; the second was the development of very high-speed nonlinear devices.

For the present discussion, the most important of the nonlinear devices is the point contact metal–oxide–metal (MOM) diode that has been adapted to achieve an extremely high speed of response by the use of small, low-resistance, low-capacitance junctions produced when the very fine tip of an etched tungsten wire is brought into contact with an oxidized nickel post. The contact area can be of the order of 10^{-11} cm^2 so that the very low capacitance and the high speed of the electrical response, thought to be due to electron tunnelling through the 8–10 Å nickel oxide layer, allows its use as a nonlinear device to mix and generate signals from d.c. up to about 200 THz ($\lambda = 1.5$ μm).

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A second type of nonlinear device, useful in the range from about 30 THz (10 μm) up to frequencies of radiation in the visible and ultraviolet, is provided by nonlinear optical crystals. These can be used for harmonic generation and signal mixing, but require a detector to produce usable electrical signals. There are important limitations in the use of crystals: firstly, the crystals have limited ranges of transparency, and secondly, because of the low nonlinear coefficients, the generated signal along a considerable path length must add up in phase in order to get usable signals, i.e. the harmonic generated 'downstream' must be in phase with the harmonic that has come from 'upstream'. Because of dispersion the phase velocity of the generating beam and the harmonic will normally differ and this in-phase adding will not occur. However, it can be accomplished in certain crystals by careful tuning of the birefringence, through changes of temperature or angle of propagation with respect to the crystal axes. Work on nonlinear optical mixing has been reviewed by Knight & Woods (1976).

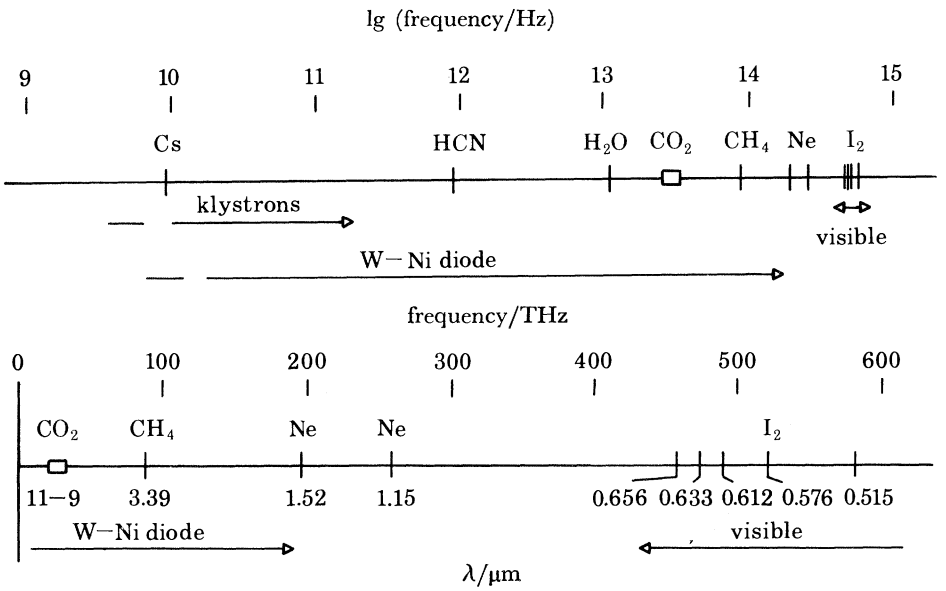

FIGURE 1. Electromagnetic spectrum from microwave to the visible radiation illustrating some important laser lines used as intermediate frequencies in extending frequency measurement to the visible. The lower, linear, scale gives a better impression of the large frequency gaps that have to be bridged.

Although the above developments have made possible the direct comparison of optical with microwave frequencies, its realization is far from simple and a great deal remains to be done to attain the promised goal of very precise measurement of visible radiation with respect to microwave standards. Problems arise from the fact that the frequencies involved are extremely high, so that even very small relative differences result in beat frequencies that are high compared with those that can be handled in convenient, 'state of the art', circuitry. This causes difficulties in two ways: small frequency instabilities in the lasers cause very large excursions in the beat. For example, a jitter of $10^{-6}f$ at 100 THz (λ = 3 μm) is 100 MHz, and if the sought-for beat signal is of this order, measurement becomes very difficult, to say the least. Secondly, matching the harmonic of one source sufficiently closely to the frequency of another source to produce low-frequency beats is not easy, because of the limited choice of reference lasers and their limited tuning range. This situation is illustrated in figure 1; the top half shows on a logarithmic scale the five decades in frequency from the caesium standard at 9 GHz to the

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visible. The ranges of klystrons and the range of operation of the W–Ni MOM diode are indicated, as well as important bench mark frequencies of Cs, HCN, H_2O, CO_2, etc. up to the I_2 lines on which HeNe and argon lasers can be stabilized by saturated absorption. Because frequency comparison depends to a considerable extent on the simple addition of frequencies, particularly at the higher ranges, and because it yields output signals that correspond to differences, the difficulties are more appropriately illustrated by the use of a linear scale, as in the bottom half of the figure. On this scale the total range of frequency comparison and measurement from sub-kilohertz, through the gigahertz microwave bands that have been made possible with recent commercial equipment development, and to the infrared region opened up by the pioneering experiments done during the 1960s at M.I.T. and elsewhere, covers only a very small part at the left of the scale. The enormous range yet to be bridged to reach the visible, as well as the large size of the gaps between available convenient lasers that provide intermediate steps, is evident.

Even in an apparently crowded region like that of the familiar 10 μm bands of CO_2 indicated on the figure, the Doppler width of about 75 MHz over which the lasers can be tuned represents only about one thousandth of line separation, so that the chance of finding a harmonic of a lower frequency close enough to a higher one so as to produce beats of a usable low frequency is rather small.

In the visible part of the spectrum the problem is greatly increased because there are no such convenient bands of laser lines and the frequency gaps are very much wider. The scarcity of benchmark laser lines can be alleviated by the use of tunable dye lasers in the visible, and, recently, of colour centre lasers in the range from *ca.* 2.5 μm to 1 μm, but problems associated with their inconvenience and instability are not trivial.

Chains to compare infrared and microwave frequencies

It is evident from the foregoing that, despite the simplicity of the basic principle, the extension of exact frequency measurement to the optical region of the spectrum is far from easy. Nevertheless the measurement of a visible frequency has been demonstrated and several accurate measurements of infrared frequency standards have been made. The latter, taken in conjunction with accurate wavelength measurements, have given the speed of light (c) to an accuracy limited by the uncertainty in the ^{86}Kr primary standard of length. This development opened the way to a redefinition of the international metre by the use of the standard for the second and the adoption by convention of a fixed, exact value for c.

The frequency measurements were made by several stages, using intermediate frequencies, so as to constitute a complete chain from the microwave to the infrared. Three examples are shown in greatly simplified form in figure 2. The first measurement of the frequency of a CH_4-stabilized HeNe laser was made at the U.S. National Bureau of Standards (N.B.S.) by Evenson *et al.* (1972). Following up the pioneering work at M.I.T. on W–Ni diodes in the far infrared, they gradually extended their use to shorter wavelengths, and succeeded in measuring the CH_4 line at 88 THz (3.39 μm), in 1972. At about the same time Bradley *et al.* (1972) at the National Physical Laboratory (N.P.L.) in London set up a similar chain and obtained results in very good agreement with N.B.S. In these chains, as shown, the output of a klystron of frequency 74 GHz was compared with an HCN laser by generation of the 12th harmonic and mixing in a conventional tungsten–silicon microwave diode. The HCN laser output was in

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turn compared with the H_2O laser line at about 10 THz by generation of its 12th harmonic and mixing in a W–Ni diode. The H_2O line was multiplied by three and compared with CO_2 laser radiation at 30 THz, again in a W–Ni diode, and finally, the 30 THz radiation was multiplied by three and compared with a CH_4-stabilized HeNe laser at 88 THz. As mentioned, this description is very much simplified: for example, at nearly all the stages above the first klystron stage, additional klystron frequencies had to be added or subtracted in the diode to reduce the output beat signal frequency to the megahertz range so as to be convenient for measuring; also, the CO_2 line used for comparison with the H_2O was not the same line that was used in the comparison with CH_4 and the difference had to be measured against a klystron-

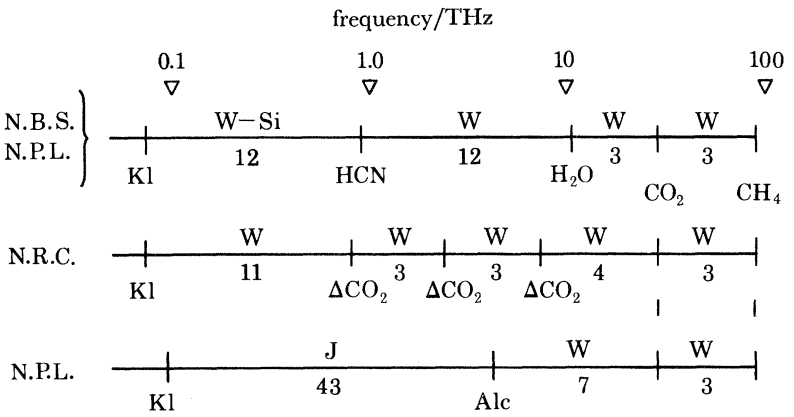

FIGURE 2. Three examples of frequency chains to relate infrared to microwave frequencies used at the U.S. National Bureau of Standards, the National Physical Laboratory and the Canadian National Research Council. They use mixing in tungsten–silicon (W–Si), tungsten–nickel (W) and Josephson junctions (J) to relate klystron (Kl) frequencies through the indicated intermediate lasers to a He-Ne laser stabilized on CH_4. 'ΔCO_2' indicates an intermediate frequency generated by the difference between two CO_2 laser transitions.

generated frequency. At N.P.L. a different pair of CO_2 lines was used in this stage. These early experiments suffered loss of accuracy in the transfer from one stage to the next, but more refined repetitions of the experiments produced frequency values for the CH_4 and CO_2 lines of accuracy better than $1:10^9$. It was these values that, taken together with wavelength measurements at N.B.S., N.P.L. and several other national laboratories, has led to the recommendation by the CIPM of 299 792 458 m s^{-1} as the best value for the speed of light. At N.R.C. the HCN and H_2O laser stages were replaced, as indicated in the figure, by the use of difference frequencies generated in W–Ni diodes by simultaneous input from two CO_2 lasers operating on appropriately chosen transitions. A considerable advantage in the simplicity of the lasers is partly offset by the low signal strengths of the difference frequencies. This required the addition of an extra stage to reduce the harmonic numbers to 3, 3 and 4. The major source of error resulted from independent operation of the separate stages; this was also true, but to a lesser extent, at N.B.S. and N.P.L. At N.R.C. this defect is being corrected by the use of simultaneous phase-locking in a new system now being set up; phase-locking of one of the stages has already been performed successfully, giving every indication that a CO_2 line, phase-locked to the caesium standard and therefore accurate to about 1 part in 10^{13}, can be realized (Whitford 1982).

In a revised version of the N.P.L. chain, the number of stages was reduced by the use of 43rd

harmonic generation in a Josephson junction, to go from a klystron to a CO_2-pumped alcohol laser at 4.25 THz; from there two stages of 7 × and 3 × were used to go via a CO_2 laser to the CH_4-stabilized HeNe laser at 88 THz (3.39 μm). In this measurement the stages were operated simultaneously and phase-locking or beat-frequency counting was used at all points to give a much higher accuracy ($3:10^{11}$) than in the first experiment.

Frequency comparison chains up to the 88 THz, CH_4-stabilized laser have now also been set up in France, Germany, Japan and the U.S.S.R., and improvements are proposed or being tested. Chebotayev (1981) recently reported phase-locking microwaves to the CH_4-stabilized laser, although only for a fraction of a second at a time.

Examples of systems designed to extend direct frequency comparison to the visible part of the spectrum are shown in very simplified schematic form in figure 3. The first of these, the N.B.S.–N.R.C. chain, was successfully demonstrated (Baird *et al.* 1979), yielding a frequency for an I_2 absorption line in the visible. The I.S.P. (Novosibirsk) system has been demonstrated to function by Chebotayev *et al.* (1976) but the component frequencies have not been measured. The third system, under development at N.B.S., has recently been operated by Pollack *et al.* (1982). Some details of these systems follow.

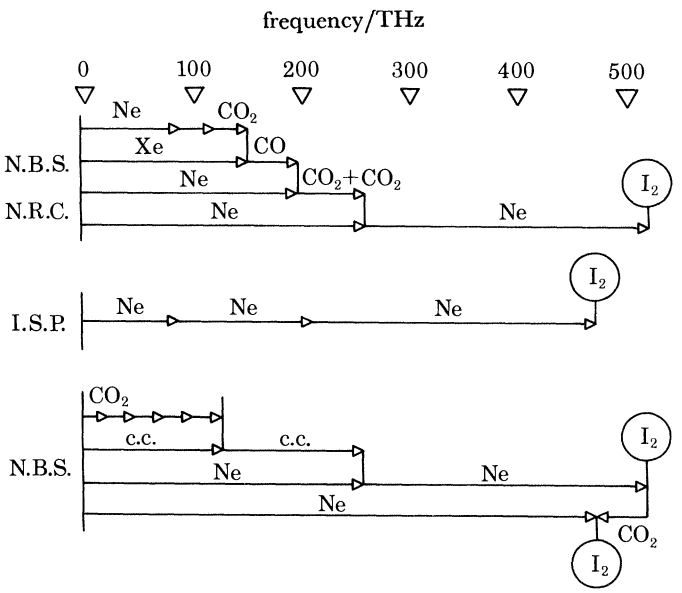

FIGURE 3. Examples of frequency chains to relate infrared to visible frequencies of I_2 by the use of Ne, Xe, CO, CO_2 and colour centre (c.c.) lasers at N.B.S., N.R.C. and I.S.P. (Institute of Semiconductor Physics, U.S.S.R.).

In the N.B.S.–N.R.C. experiments the frequency of a Xe laser at 150 THz (2.02 μm) was first measured by comparison in a W–Ni diode with the sum frequency of a HeNe laser at 3.39 μm (88 THz) and two 10 μm CO_2 lines (*ca.* 30 THz). The sum of this Xe line and a CO line at 50 THz was used to measure the 1.5 μm (196 THz) HeNe laser line, again in a W–Ni diode. In the final part of the experiment done at N.B.S., the HeNe 1.5 μm line was added in a proustite crystal to the sum of two CO_2 lines (produced by addition in a $CdGeAs_2$ crystal) resulting in a sum wavelength very near 1.15 μm. A pure Ne 1.15 μm (260 THz) laser output was compared by the use of a Schottky diode. The Ne laser, stabilized on its Lamb dip, was

taken to N.R.C. and compared with a 1.15 μm HeNe laser whose radiation, after doubling, was locked to an I_2 line by saturated absorption. This experiment, done in 1979, thus demonstrated for the first time the direct measurement of a frequency in the visible.

In the I.S.P. system three Ne transitions, at 3.39, 2.39 and 1.15 μm, were excited simultaneously in a HeNe plasma; nonlinear interaction in the plasma itself produced a sum frequency at 0.633 μm (474 THz). Although very elegant in principle the scheme has not been widely adopted because of apparent difficulties in measurement and control of the component frequencies at 3.39, 2.39 and 1.15 μm. However, Pollack *et al.* (1982) have recently demonstrated the technique in a more practical form in which a colour centre laser is substituted for the 2.39 μm line and a separate plasma tube is used for the nonlinear mixing.

The third chain shown, under development at N.B.S. (Boulder), starts with CO_2 lines whose sum frequency, generated in a W–Ni diode, is used to control at 130 THz a colour centre laser at a known frequency. The frequency of the colour centre laser is doubled to 260 THz in a $LiNbO_3$ crystal, and compared with a HeNe 1.15 μm laser. The frequency of the latter is doubled in a second $LiNbO_3$ crystal for reference to the I_2 line at 520 THz, as in the N.B.S.–N.R.C. experiment.

A number of other alternative systems are proposed or under development at other laboratories. It is emphasized that these frequency comparison systems represent, at present, rather difficult complex experiments, the apparent simplicity of the schematic diagram notwithstanding. Problems associated with phase matching, small signals, laser instability, and large frequency differences are severe. On the other hand it is now clear that very accurate measurement of visible frequencies can be realized at least for a few benchmark standards that will play an important role in spectroscopy.

The future of spectroscopic frequency standards

In view of the extension of very accurate frequency comparison techniques to the visible part of the spectrum one might well wonder about its impact on the system of spectroscopic standards and whether wavelength comparison will be replaced by the convenient sort of technology now used in the radio and microwave region for tuning, comparing and counting frequencies. There is, in fact, already a sort of 'new look' for some spectroscopic standards, measured by frequency instead of wavelength methods; this is especially true as one goes farther into the infrared. However, there are very important limitations and qualifications to any general application of frequency standards.

In the first place, frequency comparison has no advantage and is rarely used in cases involving incoherent, that is non-laser, emission radiation; tunable lasers are very practical, however, for scanning absorption lines. Secondly, there is still a major difficulty caused by the enormous frequency gaps involved in comparisons in the near infrared and shorter wavelengths where detectors and frequency mixers do not yet exist with the necessary high speed.

The realization of laser frequency standards very precisely correlated with the standard caesium frequency will be achieved either by a completely phase-locked system or by a simultaneous count of beats at some of the stages. However, this is likely to be practical in the visible for only a few benchmarks such as at 0.576 μm, 0.633 μm, probably at 0.612 μm and possibly the I_2 line near the H_α line at 0.656 μm. Once such benchmarks are established in a given part of the spectrum, either in the form of a precisely reproducible absorption line or a laser locked

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to a frequency chain, other lines or benchmarks can be measured as required by reference to them, either by wavelength interferometry or by frequency comparison. The latter may be quite difficult measurements and may require a number of steps.

The process of measuring a laser frequency has become relatively straightforward in the region where point-contact MOM diodes have a nonlinear electrical response, i.e. up to about 1.5 μm (200 THz). Differences of up to a few tens of gigahertz can be measured directly in the diode output; for greater separations, up to about 100 GHz, klystron radiation can be mixed in the diode to produce differences in the megahertz range. For yet greater separations, up to about 7 THz, two CO_2 lasers with the appropriate difference in frequency can be used; and finally, harmonics and sums of CO_2 or other appropriate laser emissions can be used to measure frequency or frequency separation upwards of 25 THz.

One example of the above process is the work of Clairon *et al.* (1980), who have established a grid of very precise standards, separated by about 50 GHz, covering a range of 265 GHz in the 10 μm region. This was done by stepping off from a well measured OsO_4 standard by the use of a klystron, to OsO_4 and SF_6 absorption lines that coincide with CO_2 laser lines. Another example of technique is the work of Siemsen (1981) at N.R.C. to measure the frequency of a laser that is well outside a grid of reference lines. When two appropriate known frequencies f_1 and f_2 are mixed with the unknown frequency f_3 the latter can be deduced from the beat frequency, $f_b = (f_1 - f_2) - (f_2 - f_3)$.

The measurement of large frequency differences gets considerably more difficult above the electrical response limit of the MOM diodes at about 1.5 μm, where nonlinear crystals must be used for harmonic generation and frequency mixing. Photoelectric detectors can be used in the measurement of differences up to several gigahertz in the region from 3 μm through the visible. Schottky diodes have also been used to measure differences up to 122 GHz by mixing with klystron-generated frequencies. In order to measure greater differences or to generate harmonics, nonlinear crystals must be generally used, although recent experiments by Drullinger *et al.* (1982) have shown that MOM diodes may be used to measure terahertz differences in the visible.

Frequency comparison by the use of nonlinear crystals is very much restricted by their limited range of transparency, and problems of phase matching and the small nonlinear coefficients; they cannot be used to mix klystron frequencies. One must hope that the number of special combinations of suitable crystals and laser lines will increase with further developments in crystal growing and in tunable dye and colour centre lasers. There is already an example where one can, in effect, transfer the 7 THz grid of CO_2 laser frequencies into the red part of the visible spectrum by mixing in proustite crystals.

Special tricks can be used to increase the measurement separation limit beyond that imposed by the photoelectric detector. One such is that suggested by Hänsch & Wong (1980), whereby a widely tunable laser is frequency-modulated so as to match the sideband separation to the intermode spacing; a comb of frequencies covering about 0.5 THz in the visible may be generated and locked to an absorption reference by two-photon absorption. Another example is the stepping procedure proposed by Burghardt *et al.* (1979). Using two stabilized dye lasers, they plan to make 200 steps of 80 GHz each in order to measure the H_α line with respect to the 0.633 μm I_2 laser line.

As is evident from the foregoing examples, although the direct measurement of frequencies in the optical region is possible, at present it involves the use of individual ingenious and difficult

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experiments, particularly in the visible spectrum. It may not be an unreasonable hope that development of new devices, perhaps a broad-band nonlinear reflector, will make possible the 'day-to-day' use in the optical region of the great accuracy and convenience inherent in the methods of frequency comparison. However, for some time to come the best means for interpolation or extrapolation with respect to relatively few very accurate benchmarks will be by the use of wavelength interferometry; this is certainly the most convenient for accuracies of $1:10^8$ or less.

Recently a number of important improvements in the technique of wavelength comparison have occurred (see Rowley 1981). First, scanning interferometers with a laser to provide a linear scale have been made. In the form of a 'lambdameter', they provide rapid measurement of a single wavelength, such as from a laser. In the form of Fourier spectrometers the wavelength of many lines, either emission or absorption, can be determined from a single recorded interferogram. Secondly, the use of servo-control to tune lasers to cavity resonances and of frequency (beat) methods to measure small differences has yielded very great sensitivity. This, together with improved steps to eliminate systematic errors, such as the use of mode matching, has led to wavelength comparisons of laser radiations well beyond 10^{10} accuracy in the best experiments – useful to complement frequency techniques. Another important technique is the translation of infrared wavelengths to the visible through mixing of radiations in nonlinear crystals so that wavelength comparison can be done with smaller diffraction errors.

Wavelength comparison techniques such as the above will undoubtedly provide the most convenient means of interpolation between the precise benchmarks established by frequency measurements. Cases are rare where absolute accuracies greater than 1 in 10^8 are required in spectroscopy, and convenience will favour wavelength techniques for some time to come.

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Discussion

W. R. C. Rowley (*National Physical Laboratory, Teddington, U.K.*). In his talk, Dr Baird pointed out that spectroscopists working in different areas specify their radiations in different units. In the microwave region one uses frequency units, in the infrared wavenumbers, and in the visible wavelengths. Now, as Dr Baird has just explained, frequency techniques may be used in all these spectral regions, and appropriate frequency standard radiations are being established. Is it not time to consider changing to a common unit to specify radiations? It would seem that the terahertz (THz) has a convenient magnitude in this respect.

K. M. Baird. I think it is indeed time to consider changing to a common unit to specify radiations, and I agree with Dr Rowley that the terahertz has a convenient magnitude.

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