

## Heterodyne Frequency Measurements of $^{12}\text{C}^{16}\text{O}$ Laser Transitions near $2050\text{ cm}^{-1}$

M. SCHNEIDER<sup>1</sup> AND J. S. WELLS

*Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80303*

AND

A. G. MAKI

*Department of Chemistry, University of Washington, Seattle, Washington 98195*

New heterodyne frequency measurements of  $^{12}\text{C}^{16}\text{O}$  laser transitions were made in the 1995 to  $2082\text{ cm}^{-1}$  (59.81 to 62.39 THz) region. Frequencies of 23 transitions (with lower vibrational quantum numbers,  $v''$ , ranging from 1 to 4) were measured. New constants for these low-lying vibrational levels were determined by fitting these data (along with sub-Doppler measurements by Pollock *et al.* (*J. Mol. Spectrosc.* **99**, 357-368 (1983)), rotational transition measurements, and FTS measurements from Guelachvili *et al.* (*J. Mol. Spectrosc.* **98**, 64-79 (1983)) to the Dunham expression. Frequency calibration tables calculated from these new constants are reported. These tables provide accurate transition frequencies for the CO laser stabilized to the Doppler-broadened gain profile. © 1990 Academic Press, Inc.

### INTRODUCTION

Frequency measurements, based on the use of  $\text{CO}_2$  lasers as frequency standards, have recently been reported (1) for CO laser transitions. The impetus for that work was provided by the development of a technique to lock the CO laser to the optogalvanic Lamb dip of the CO molecule on many lasing transitions (2). This facilitated a more accurate determination of CO transition frequencies than former Fourier transform spectroscopy (FTS) measurements (3, 4), although the frequency measurements were restricted to the spectral region where typical CO lasers readily oscillate ( $6 \leq v'' \leq 34$ ). Based on these measurements, frequency tables for lower vibrational bands could only be extrapolated. Consequently, their predicted frequencies were less accurate than those for higher vibrational bands.

Over the past several years heterodyne frequency measurements on linear triatomic molecules (for example,  $\text{N}_2\text{O}$  and  $\text{OCS}$ ) have been made as part of a continuing project from the National Institute of Standards and Technology in Boulder and Gaithersburg to generate frequency calibration tables for the infrared region. In many of these experiments a CO laser was used as a transfer oscillator to refer the unknown frequency of a tunable diode laser to  $\text{CO}_2$  laser frequency standards (for details refer to Refs. (5, 6)). The frequency of the CO laser transition was not essential for such

<sup>1</sup> Guest worker from Institut für Angewandte Physik der Universität Bonn, D 5300, West Germany.

0022-2852/90 \$3.00

Copyright © 1990 by Academic Press, Inc.  
All rights of reproduction in any form reserved.

measurements. Rather, the measurements depended on the transfer oscillator frequency, which could have been anywhere near the peak of the gain curve. Nevertheless, the CO transition frequency was determined as a by-product in order to provide accurate CO laser frequencies for the CO laser community. However, reporting these CO laser frequencies has been discontinued, since the more accurate data from Ref. (1) are now available.

In a new set of heterodyne measurements (7) a redesigned CO laser was used as transfer oscillator. This new laser operated on low-lying vibrational levels where an "ordinary" CO laser typically does not oscillate. We achieved oscillation as high in frequency as 62.39 THz ( $P_1(9)$ ).<sup>2</sup> We report here measurements of the Doppler-limited frequencies of the high frequency CO laser transitions. These measurements provide frequencies, measured against CO<sub>2</sub> laser frequency standards, for the low-lying vibrational bands of CO.

The transition frequencies were fitted to the Dunham expression for rovibrational constants while other CO frequency measurements (8, 9) were simultaneously taken into account. Based on these constants, tables of frequencies for possible CO lasing transitions are reported for the transitions having vibrational quantum numbers  $v'' = 0$  to  $v'' = 6$ . These tables, combined with those in Ref. (10), provide complete coverage over possible CO laser spectra. These tables are based primarily on heterodyne frequency measurements against CO<sub>2</sub> laser frequency standards.

#### EXPERIMENTAL DETAILS

The CO laser used for the present measurements operates under liquid nitrogen-cooled flowing-gas conditions. The resonator consists of a 240 lines/mm high-efficiency grating and a dielectric coupling mirror (98% reflective at 5  $\mu\text{m}$ ) with a 10-m radius of curvature. CW laser operation on vibrational bands as low as  $v'' = 1$  was achieved and output power of a few milliwatts was measured on the weaker lines.

The CO laser frequency was referred to two CO<sub>2</sub> laser frequency standards by mixing the radiation from the CO laser and the CO<sub>2</sub> lasers on a MIM diode. Occasionally, a microwave frequency was also coupled to the diode to convert the beat note into the frequency region below 1 GHz which was accessible to our rf equipment. For details of this heterodyne technique, refer to Refs. (5, 6).

We measured the 23 CO laser transitions given in Table I. The uncertainty in the measurement (3 MHz) was determined by the width of the Doppler-broadened gain profile of the CO laser.

The frequencies of two CO  $v = 1-0$  transitions have also been measured and are given at the bottom of Table I. For these measurements a tunable diode laser (TDL) was locked to the  $P_0(18)$  (or  $P_0(31)$ ) absorption in a low-pressure CO cell. The diode laser frequency was determined by heterodyning against a CO laser transfer oscillator operating on the  $P_1(12)$  (or  $P_3(14)$ ) transition. The frequency of the transfer oscillator was in turn measured against two CO<sub>2</sub> laser standards. Details of the TDL frequency measurements are available elsewhere (5, 6).

<sup>2</sup> We follow the convention where  $P_v(J'')$  denotes transitions, with  $J''$  and  $v''$  being the rotational and vibrational quantum numbers of the lower state.

TABLE I  
Heterodyne Frequency Measurements on  $^{12}\text{C}^{16}\text{O}$ .

CO Transition $P_{v''}(J'')$	Observed <sup>a</sup> Frequency [MHz]	Calculated		Obs.-Calc. [MHz]
		Frequency [MHz]	Wavenumber [ $\text{cm}^{-1}$ ]	
$P_4(11)$	59 811 747.50	59 811 749.23	1995.105 31	-1.73
$P_4(10)$	59 933 071.30	59 933 071.98	1999.152 20	-0.68
$P_4(9)$	60 053 387.80	60 053 389.62	2003.165 57	-1.82
$P_4(14)$	60 214 872.90	60 214 871.58	2008.552 03	1.32
$P_3(7)$	60 290 990.10	60 290 992.05	2011.091 13	-1.95
$P_4(13)$	60 340 233.21	60 340 233.81	2012.733 66	-0.60
$P_3(12)$	60 464 604.60	60 464 604.01	2016.882 20	0.59
$P_3(11)$	60 587 978.00	60 587 977.80	2020.997 51	0.20
$P_3(10)$	60 710 350.10	60 710 350.79	2025.079 44	-0.69
$P_3(9)$	60 831 718.20	60 831 718.57	2029.127 83	-0.37
$P_3(8)$	60 952 077.10	60 952 076.77	2033.142 55	0.33
$P_3(7)$	61 071 422.90	61 071 420.98	2037.123 44	1.92
$P_2(13)$	61 116 439.50	61 116 437.90	2038.625 04	1.60
$P_2(12)$	61 241 858.90	61 241 858.47	2042.808 62	0.43
$P_2(11)$	61 366 283.80	61 366 282.55	2046.958 96	1.25
$P_2(10)$	61 489 706.37	61 489 705.73	2051.075 92	0.64
$P_2(9)$	61 612 123.87	61 612 123.64	2055.159 34	0.23
$P_2(8)$	61 733 533.40	61 733 531.87	2059.209 08	1.53
$P_2(13)$	61 894 667.40	61 894 667.70	2064.584 00	-0.30
$P_1(12)$	62 021 140.60	62 021 138.55	2068.802 61	2.05
$P_1(11)$	62 146 613.40	62 146 612.85	2072.987 98	0.55
$P_1(10)$	62 271 086.60	62 271 086.19	2077.139 97	0.41
$P_1(9)$	62 394 555.00	62 394 554.18	2081.258 42	0.82
$P_0(31)$	60 214 073.80	60 214 078.70	2008.525 58	-4.90
$P_0(18)$	62 022 472.10	62 022 472.15	2068.847 09	-0.05

<sup>a</sup> The uncertainty in the frequency measurements is 3 MHz except for  $P_0(18)$  and  $P_0(31)$  which are uncertain by 4 MHz and 5 MHz respectively.

#### ANALYSIS AND RESULTS

The goal of our work was to provide accurate CO laser transition frequencies for the vibrational bands with  $v'' \leq 6$ . To achieve this goal it was necessary to include all other frequency measurements on the lower vibrational states of CO in addition to the 23 new CO frequencies given by this work. Included in the fit were the heterodyne measurements due to Pollock *et al.* (8), where the first overtone band had been measured, mostly with sub-Doppler accuracy. The rotational transitions reported by Nolt *et al.* (9) were also included, as were the 10 transitions from Ref. (1) with  $v'' = 6$  and 7.

The data were combined in a least-squares fit to determine the best set of Dunham rovibrational constants to define the energy levels and transitions according to the usual equation

$$E(v, J) = \sum_{i,j} Y_{ij}(v + 1/2)^i (J(J + 1))^j. \quad (1)$$

In this fit the measurements were weighted by the inverse squares of their estimated uncertainties.

The most comprehensive set of spectroscopic measurements on the  $v'' = 0$  to 7 levels of CO are the FTS measurements by Guelachvili *et al.* (4). Although these FTS data deviate systematically from other measurements by as much as 10 MHz (1, 11, 12), they provide data for a broad range of rotational quantum numbers.

In our analysis of the spectra of  $N_2O$  and  $OCS$  (6, 7) we used a technique of fitting FTS data with heterodyne frequency measurements in such a way as to allow for a fixed calibration error on all the FTS data that a single suite of measurements comprises. This technique was also used to allow us to include the FTS data on the lower vibrational levels of CO without compromising the accuracy of the heterodyne measurements.

The CO transitions from the FTS measurements (Ref. (4), dataset number 1568, "type B source") were added to the least-squares fit to the Dunham expression. A separate set of FTS measurements by Guelachvili (3) on the 1-0 and 2-1 bands was also included in the fit. The fit included a different frequency calibration factor for each set of FTS data. Only vibrational transitions for  $v'' \leq 7$  were used. The frequency calibration factor for the data from Ref. (4) was 0.999999876(3), which was equivalent to subtracting 7 MHz from the FTS measurements at  $2000 \text{ cm}^{-1}$ . The calibration factor used for the data from Ref. (3) was 0.999999816(4) or about 11 MHz.

Some of the higher order terms,  $Y_{13}$ ,  $Y_{04}$ ,  $Y_{14}$ , and  $Y_{05}$ , could not be determined by a fit of the data to a simple power series like Eq. (1), but their values could be determined by a fit of the data to a Dunham potential function. For vibrational states close to the bottom of the potential well, those constants are given quite reliably by such a potential function because they only depend on  $B_e$ ,  $\omega_e$ ,  $a_1$ ,  $a_2$ ,  $a_3$ , and  $a_4$ , which are all well determined. In the least-squares fit to obtain the rovibrational constants, those higher-order constants were fixed at the values given by a preliminary fit of the same data set to a Dunham potential function, as was done in Ref. (13).

Table II gives the rovibrational constants determined for CO from this analysis. The values for some of the  $Y_{ij}$  constants are slightly different from those determined by previous workers (1, 4) because we used a data set covering only low-lying vibrational levels.

TABLE II  
Dunham Coefficients for  $^{12}C^{16}O$  in MHz.

$Y_{10} \times 10^{-8}$	0.650 493 510 6(216) <sup>a</sup>
$Y_{20} \times 10^{-6}$	-0.398 362 273(1469)
$Y_{30} \times 10^{-3}$	0.312 265(406)
$Y_{40} \times 10^{-1}$	0.211 33(488)
$Y_{50} \times 10^{-5}$	0.005(210)
$Y_{01} \times 10^{-3}$	0.578 983 404 3(335)
$Y_{11} \times 10^{-1}$	-0.524 753 59(304)
$Y_{21} \times 10^1$	0.134 29(1194)
$Y_{31} \times 10^3$	0.973 6(790)
$Y_{02} \times 10^4$	-0.183 520 22(574)
$Y_{12} \times 10^5$	0.287 5(218)
$Y_{22} \times 10^5$	-0.533 2(728)
$Y_{03} \times 10^6$	0.177 78(296)
$Y_{13} \times 10^{11}$	[-0.436 1(9)] <sup>b</sup>
$Y_{04} \times 10^{13}$	[-0.108 218(6)]
$Y_{14} \times 10^{17}$	[-0.205 2(14)]
$Y_{05} \times 10^{17}$	[-0.141 3(5)]

- a) The uncertainty in the last digits (twice the standard error) is given in parentheses.  
b) The constants given in square brackets were given by a fit of the potential function (see text).

TABLE III  
Calculated Frequencies of  $^{12}\text{C}^{16}\text{O}$  Laser Transitions.

	Frequency [MHz]	Wavenumber [ $\text{cm}^{-1}$ ]	Frequency [MHz]	Wavenumber [ $\text{cm}^{-1}$ ]
	vibrational band v=1-0		vibrational band v=2-1	
P(3)	63 904 707.6(05) <sup>a</sup>	2131.631 72(02)	63 114 003.3(05)	2105.256 66(02)
P(4)	63 786 314.5(05)	2127.682 55(02)	62 996 659.8(05)	2101.342 50(02)
P(5)	63 666 889.6(05)	2123.698 96(02)	62 878 284.6(05)	2097.393 93(02)
P(6)	63 546 437.2(05)	2119.681 10(02)	62 758 882.0(05)	2093.411 09(02)
P(7)	63 424 961.8(05)	2115.629 12(02)	62 638 456.5(05)	2089.394 12(02)
P(8)	63 302 467.8(05)	2111.543 16(02)	62 517 012.4(04)	2085.343 18(01)
P(9)	63 178 959.6(05)	2107.423 37(02)	62 394 554.2(04)	2081.258 42(01)
P(10)	63 054 441.5(05)	2103.269 89(02)	62 271 086.2(04)	2077.139 97(01)
P(11)	62 928 918.1(04)	2099.082 88(01)	62 146 612.8(04)	2072.987 98(01)
P(12)	62 802 393.7(04)	2094.862 48(01)	62 021 138.6(04)	2068.802 61(01)
P(13)	62 674 872.6(04)	2090.608 83(01)	61 894 667.7(04)	2064.584 00(01)
P(14)	62 546 359.4(04)	2086.322 09(01)	61 767 204.7(04)	2060.332 29(01)
P(15)	62 416 858.3(04)	2082.002 40(01)	61 638 753.9(04)	2056.047 63(01)
P(16)	62 286 373.8(04)	2077.649 91(01)	61 509 319.7(04)	2051.730 17(01)
P(17)	62 154 910.3(04)	2073.264 76(01)	61 378 906.6(04)	2047.380 06(01)
P(18)	62 022 472.2(04)	2068.847 09(01)	61 247 518.9(04)	2042.997 43(01)
P(19)	61 889 063.8(05)	2064.397 07(02)	61 115 160.9(04)	2038.582 45(01)
P(20)	61 754 689.5(05)	2059.914 83(02)	60 981 837.1(05)	2034.135 24(02)
	vibrational band v=3-2		vibrational band v=4-3	
P(3)	62 325 273.8(08)	2078.947 47(03)	61 538 569.9(10)	2052.705 85(03)
P(4)	62 208 980.0(07)	2075.068 33(02)	61 423 325.7(10)	2048.861 72(03)
P(5)	62 091 654.5(07)	2071.154 77(02)	61 307 049.8(10)	2044.983 17(03)
P(6)	61 973 301.7(07)	2067.206 94(02)	61 189 746.8(09)	2041.070 37(03)
P(7)	61 853 926.0(07)	2063.225 00(02)	61 071 421.0(09)	2037.123 44(03)
P(8)	61 733 531.9(07)	2059.209 08(02)	60 952 076.8(09)	2033.142 55(03)
P(9)	61 612 123.6(06)	2055.159 34(02)	60 831 718.6(09)	2029.127 83(03)
P(10)	61 489 705.7(06)	2051.075 92(02)	60 710 350.8(08)	2025.079 44(03)
P(11)	61 366 282.5(06)	2046.958 96(02)	60 587 977.8(08)	2020.997 51(03)
P(12)	61 241 858.5(06)	2042.808 62(02)	60 464 604.0(08)	2016.882 20(03)
P(13)	61 116 437.9(06)	2038.625 04(02)	60 340 233.8(08)	2012.733 66(03)
P(14)	60 990 025.2(06)	2034.408 37(02)	60 214 871.6(08)	2008.552 03(03)
P(15)	60 862 624.9(06)	2030.158 75(02)	60 088 521.7(08)	2004.337 45(03)
P(16)	60 734 241.2(06)	2025.876 33(02)	59 961 188.6(08)	2000.090 07(03)
P(17)	60 604 878.5(06)	2021.561 26(02)	59 832 876.6(08)	1995.810 05(03)
P(18)	60 474 541.3(06)	2017.213 68(02)	59 703 590.2(09)	1991.497 51(03)
P(19)	60 343 234.0(06)	2012.833 74(02)	59 573 333.6(09)	1987.152 62(03)
P(20)	60 210 960.9(07)	2008.421 58(02)	59 442 111.3(09)	1982.775 52(03)

<sup>a</sup> The estimated uncertainty (three times the standard error) in the last digits is given in parentheses. We believe these uncertainties should be treated as one standard error on the absolute values.

Table III gives the frequencies for possible CO laser transitions, based on the constants in Table II. The variance-covariance matrix given by the least-squares fit was used to estimate the uncertainty of the calculated frequencies (given in parentheses in Table III). The statistically determined uncertainties seem to us to be too optimistic in terms of absolute frequency accuracy so we have reported 3 times the standard error, which is closer to our estimate of the accuracy of the calculated frequencies.

The calculated frequencies given in Table III deviate from Guelachvili's measurements (3, 4, 14) by as much as 11 MHz, as might have been expected from previous works (1, 10-12). The frequencies also differ from those given in Ref. (10) by slightly more than 4 MHz in the case of the  $v = 3-2$  transitions. The  $v = 1-0$  fundamental transitions are in very good agreement with those measured by Brown and Toth (11).

Table III  
Calculated frequencies of  $^{12}\text{C}^{16}\text{O}$  laser transitions

	Frequency [MHz]	Wavenumber [ $\text{cm}^{-1}$ ]	Frequency [MHz]	Wavenumber [ $\text{cm}^{-1}$ ]
	vibrational band v=1-0		vibrational band v=2-1	
P(3)	63 904 707.6(05) <sup>a</sup>	2131.631 60(02)	63 114 003.3(05)	2105.256 54(02)
P(4)	63 786 314.5(05)	2127.682 43(02)	62 996 659.8(05)	2101.342 38(02)
P(5)	63 666 889.6(05)	2123.698 84(02)	62 878 284.6(05)	2097.393 81(02)
P(6)	63 546 437.2(05)	2119.680 98(02)	62 758 882.0(05)	2093.410 97(02)
P(7)	63 424 961.8(05)	2115.629 00(02)	62 638 456.5(05)	2089.394 01(02)
P(8)	63 302 467.8(05)	2111.543 04(02)	62 517 012.4(04)	2085.343 07(01)
P(9)	63 178 959.6(05)	2107.423 25(02)	62 394 554.2(04)	2081.258 30(01)
P(10)	63 054 441.5(05)	2103.269 77(02)	62 271 086.2(04)	2077.139 85(01)
P(11)	62 928 918.1(04)	2099.082 76(01)	62 146 612.8(04)	2072.987 87(01)
P(12)	62 802 393.7(04)	2094.862 36(01)	62 021 138.6(04)	2068.802 50(01)
P(13)	62 674 872.6(04)	2090.608 72(01)	61 894 667.7(04)	2064.583 88(01)
P(14)	62 546 359.4(04)	2086.321 98(01)	61 767 204.7(04)	2060.332 17(01)
P(15)	62 416 858.3(04)	2082.002 29(01)	61 638 753.9(04)	2056.047 52(01)
P(16)	62 286 373.8(04)	2077.649 79(01)	61 509 319.7(04)	2051.730 06(01)
P(17)	62 154 910.3(04)	2073.264 64(01)	61 378 906.6(04)	2047.379 94(01)
P(18)	62 022 472.2(04)	2068.846 98(01)	61 247 518.9(04)	2042.997 32(01)
P(19)	61 889 063.8(05)	2064.396 96(02)	61 115 160.9(04)	2038.582 33(01)
P(20)	61 754 689.5(05)	2059.914 71(02)	60 981 837.1(05)	2034.135 13(02)
	vibrational band v=3-2		vibrational band v=4-3	
P(3)	62 325 273.8(08)	2078.947 36(03)	61 538 569.9(10)	2052.705 74(03)
P(4)	62 208 980.0(07)	2075.068 21(02)	61 423 325.7(10)	2048.861 61(03)
P(5)	62 091 654.5(07)	2071.154 65(02)	61 307 049.8(10)	2044.983 06(03)
P(6)	61 973 301.7(07)	2067.206 83(02)	61 189 746.8(09)	2041.070 25(03)
P(7)	61 853 926.0(07)	2063.224 89(02)	61 071 421.0(09)	2037.123 33(03)
P(8)	61 733 531.9(07)	2059.208 97(02)	60 952 076.8(09)	2033.142 43(03)
P(9)	61 612 123.6(06)	2055.159 23(02)	60 831 718.6(09)	2029.127 72(03)
P(10)	61 489 705.7(06)	2051.075 81(02)	60 710 350.8(08)	2025.079 32(03)
P(11)	61 366 282.5(06)	2046.958 85(02)	60 587 977.8(08)	2020.997 40(03)
P(12)	61 241 858.5(06)	2042.808 51(02)	60 464 604.0(08)	2016.882 09(03)
P(13)	61 116 437.9(06)	2038.624 93(02)	60 340 233.8(08)	2012.733 55(03)
P(14)	60 990 025.2(06)	2034.408 26(02)	60 214 871.6(08)	2008.551 92(03)
P(15)	60 862 624.9(06)	2030.158 64(02)	60 088 521.7(08)	2004.337 34(03)
P(16)	60 734 241.2(06)	2025.876 22(02)	59 961 188.6(08)	2000.089 96(03)
P(17)	60 604 878.5(06)	2021.561 15(02)	59 832 876.6(08)	1995.809 94(03)
P(18)	60 474 541.3(06)	2017.213 57(02)	59 703 590.2(09)	1991.497 40(03)
P(19)	60 343 234.0(06)	2012.833 62(02)	59 573 333.6(09)	1987.152 51(03)
P(20)	60 210 960.9(07)	2008.421 47(02)	59 442 111.3(09)	1982.775 41(03)

<sup>a</sup> The estimated uncertainty (three times the standard error) in the last digits is given in parentheses. We believe these uncertainties should be treated as one standard error on the absolute values.

Table III (cont.):

	Frequency [MHz]	Wavenumber [cm <sup>-1</sup> ]	Frequency [MHz]	Wavenumber [cm <sup>-1</sup> ]
	vibrational band v=5-4		vibrational band v=6-5	
P(3)	60 753 942.3(11) <sup>a</sup>	2026.533 38(04)	59 971 441.6(10)	2000.431 97(03)
P(4)	60 639 747.6(10)	2022.724 25(03)	59 858 296.3(10)	1996.657 85(03)
P(5)	60 524 521.3(10)	2018.880 72(03)	59 744 119.7(10)	1992.849 32(03)
P(6)	60 408 268.0(10)	2015.002 93(03)	59 628 916.1(10)	1989.006 54(03)
P(7)	60 290 992.0(10)	2011.091 02(03)	59 512 689.9(09)	1985.129 66(03)
P(8)	60 172 697.8(09)	2007.145 15(03)	59 395 445.5(09)	1981.218 81(03)
P(9)	60 053 389.6(09)	2003.165 46(03)	59 277 187.4(08)	1977.274 14(03)
P(10)	59 933 072.0(09)	1999.152 09(03)	59 157 919.9(08)	1973.295 80(03)
P(11)	59 811 749.2(09)	1995.105 20(03)	59 037 647.4(07)	1969.283 95(02)
P(12)	59 689 425.8(08)	1991.024 93(03)	58 916 374.4(07)	1965.238 71(02)
P(13)	59 566 106.0(08)	1986.911 43(03)	58 794 105.1(06)	1961.160 25(02)
P(14)	59 441 794.3(08)	1982.764 83(03)	58 670 844.0(06)	1957.048 70(02)
P(15)	59 316 495.0(08)	1978.585 30(03)	58 546 595.4(06)	1952.904 21(02)
P(16)	59 190 212.6(08)	1974.372 97(03)	58 421 363.8(06)	1948.726 94(02)
P(17)	59 062 951.4(08)	1970.128 00(03)	58 295 153.5(06)	1944.517 01(02)
P(18)	58 934 715.8(09)	1965.850 52(03)	58 167 968.9(06)	1940.274 59(02)
P(19)	58 805 510.2(09)	1961.540 68(03)	58 039 814.3(06)	1935.999 81(02)
P(20)	58 675 338.9(09)	1957.198 63(03)	57 910 694.2(06)	1931.692 83(02)
	vibrational band v=7-6		ERRATUM	
P(3)	59 191 118.7(11)	1974.403 19(04)	<p>Volume 139, number 2 (1990): M. Schneider, J. S. Wells, and A. G. Maki, "Heterodyne Frequency Measurements of <sup>12</sup>C<sup>16</sup>O Laser Transitions near 2050 cm<sup>-1</sup>," pp. 432-438.</p> <p>Due to a problem with properly defining a double precision variable, the wavenumber entries in Tables I and III were too high by approximately 0.00011 cm<sup>-1</sup>. A corrected version of Table III (which encompasses all wave- number values in Table I) is given here. We wish to thank A. Fayt for drawing our attention to this error.</p>	
P(4)	59 079 022.8(11)	1970.664 08(04)		
P(5)	58 965 895.6(11)	1966.890 56(04)		
P(6)	58 851 741.6(10)	1963.082 79(03)		
P(7)	58 736 565.2(10)	1959.240 92(03)		
P(8)	58 620 370.7(09)	1955.365 09(03)		
P(9)	58 503 162.6(09)	1951.455 45(03)		
P(10)	58 384 945.3(08)	1947.512 14(03)		
P(11)	58 265 723.1(07)	1943.535 32(02)		
P(12)	58 145 500.4(07)	1939.525 12(02)		
P(13)	58 024 281.6(06)	1935.481 70(02)		
P(14)	57 902 071.2(05)	1931.405 20(02)		
P(15)	57 778 873.4(04)	1927.295 76(01)		
P(16)	57 654 692.6(04)	1923.153 54(01)		
P(17)	57 529 533.3(04)	1918.978 67(01)		
P(18)	57 403 399.8(04)	1914.771 31(01)		
P(19)	57 276 296.5(04)	1910.531 60(01)		
P(20)	57 148 227.7(04)	1906.259 69(01)		

<sup>a</sup> The estimated uncertainty (three times the standard error) in the last digits is given in parentheses. We believe these uncertainties should be treated as one standard error on the absolute values.

TABLE III—Continued

	Frequency [MHz]	Wavenumber [cm <sup>-1</sup> ]	Frequency [MHz]	Wavenumber [cm <sup>-1</sup> ]
	vibrational band v=5-4		vibrational band v=6-5	
P(3)	60 753 942.3(11) <sup>a</sup>	2026.533 49(04)	59 971 441.6(10)	2000.432 08(03)
P(4)	60 639 747.6(10)	2022.724 36(03)	59 858 296.3(10)	1996.657 96(03)
P(5)	60 524 521.3(10)	2018.880 83(03)	59 744 119.7(10)	1992.849 43(03)
P(6)	60 408 268.0(10)	2015.003 04(03)	59 628 916.1(10)	1989.006 65(03)
P(7)	60 290 992.0(10)	2011.091 13(03)	59 512 689.9(09)	1985.129 77(03)
P(8)	60 172 697.8(09)	2007.145 26(03)	59 395 445.5(09)	1981.218 91(03)
P(9)	60 053 389.6(09)	2003.165 57(03)	59 277 187.4(08)	1977.274 25(03)
P(10)	59 933 072.0(09)	1999.152 20(03)	59 157 919.9(08)	1973.295 91(03)
P(11)	59 811 749.2(09)	1995.105 31(03)	59 037 647.4(07)	1969.284 05(02)
P(12)	59 689 425.8(08)	1991.025 04(03)	58 916 374.4(07)	1965.238 82(02)
P(13)	59 566 106.0(08)	1986.911 54(03)	58 794 105.1(06)	1961.160 35(02)
P(14)	59 441 794.3(08)	1982.764 94(03)	58 670 844.0(06)	1957.048 81(02)
P(15)	59 316 495.0(08)	1978.585 41(03)	58 546 595.4(06)	1952.904 32(02)
P(16)	59 190 212.6(08)	1974.373 08(03)	58 421 363.8(06)	1948.727 04(02)
P(17)	59 062 951.4(08)	1970.128 10(03)	58 295 153.5(06)	1944.517 12(02)
P(18)	58 934 715.8(09)	1965.850 62(03)	58 167 968.9(06)	1940.274 70(02)
P(19)	58 805 510.2(09)	1961.540 79(03)	58 039 814.3(06)	1935.999 92(02)
P(20)	58 675 338.9(09)	1957.198 74(03)	57 910 694.2(06)	1931.692 94(02)
	vibrational band v=7-6			
P(3)	59 191 118.7(11)	1974.403 30(04)		
P(4)	59 079 022.8(11)	1970.664 19(04)		
P(5)	58 965 895.6(11)	1966.890 67(04)		
P(6)	58 851 741.6(10)	1963.082 90(03)		
P(7)	58 736 565.2(10)	1959.241 03(03)		
P(8)	58 620 370.7(09)	1955.365 20(03)		
P(9)	58 503 162.6(09)	1951.455 56(03)		
P(10)	58 384 945.3(08)	1947.512 25(03)		
P(11)	58 265 723.1(07)	1943.535 43(02)		
P(12)	58 145 500.4(07)	1939.525 23(02)		
P(13)	58 024 281.6(06)	1935.481 81(02)		
P(14)	57 902 071.2(05)	1931.405 30(02)		
P(15)	57 778 873.4(04)	1927.295 87(01)		
P(16)	57 654 692.6(04)	1923.153 64(01)		
P(17)	57 529 533.3(04)	1918.978 78(01)		
P(18)	57 403 399.8(04)	1914.771 42(01)		
P(19)	57 276 296.5(04)	1910.531 71(01)		
P(20)	57 148 227.7(04)	1906.259 79(01)		

## CONCLUSION

Doppler-limited heterodyne frequency measurements have been made for CO laser transitions for vibrational quantum numbers with  $v'' \leq 4$ . These data were fitted to the Dunham formula, simultaneously taking into account other frequency measurements. FTS measurements given by Guelachvili were included in such a way as not to affect the  $Y_{10}$  constant. The frequencies for the low-lying vibrational bands were calculated yielding accurate tables of CO laser transition frequencies. These tables provide frequencies accurate enough for Doppler-limited stabilized CO lasers.

Work on a CO laser, which oscillates on the fundamental transitions ( $v = 1-0$ ) and is stabilized by locking to the absorption of the CO molecule in a low pressure cell, is in progress at the Institut für Angewandte Physik in Bonn. This should provide even better calibration standards in the mid-infrared comparable to the data from the overtone transitions measured by Pollock *et al.* (8).



## ACKNOWLEDGMENTS

We are grateful to G. Guelachvili for providing the magnetic tape with the data from his Fourier transform experiments. Also, we thank D. A. Jennings for providing his computer program to calculate the frequency synthesis schemes. This work was supported in part by the Upper Atmospheric Research Office of NASA.

RECEIVED: October 20, 1989

## REFERENCES

1. M. SCHNEIDER, K. M. EVENSON, M. D. VANEK, D. A. JENNINGS, J. S. WELLS, A. STAHN, AND W. URBAN, *J. Mol. Spectrosc.* **135**, 197-206 (1989).
2. M. SCHNEIDER, A. HINZ, A. GROH, K. M. EVENSON, AND W. URBAN, *Appl. Phys. B*, **44**, 241-245 (1987).
3. G. GUELACHVILI, *J. Mol. Spectrosc.* **75**, 251-269 (1979).
4. G. GUELACHVILI, D. DE VILLENEUVE, R. FARRENQ, W. URBAN, AND J. VERGES, *J. Mol. Spectrosc.* **98**, 64-79 (1983).
5. J. S. WELLS, F. R. PETERSEN, AND A. G. MAKI, *J. Mol. Spectrosc.* **98**, 404-412 (1983).
6. J. S. WELLS, D. A. JENNINGS, A. HINZ, J. S. MURRAY, AND A. G. MAKI, *J. Opt. Soc. Amer. B* **2**, 857-861 (1985).
7. J. S. WELLS, M. SCHNEIDER, AND A. G. MAKI, to be submitted for publication.
8. C. R. POLLOCK, F. R. PETERSEN, D. A. JENNINGS, J. S. WELLS, AND A. G. MAKI, *J. Mol. Spectrosc.* **99**, 357-368 (1983).
9. I. G. NOLT, J. V. RADOSTITZ, K. M. EVENSON, D. A. JENNINGS, K. R. LEOPOLD, M. D. VANEK, L. R. ZINK, A. HINZ, AND K. V. CHANCE, *J. Mol. Spectrosc.* **125**, 274-287 (1987).
10. M. SCHNEIDER, K. M. EVENSON, M. D. VANEK, D. A. JENNINGS, J. S. WELLS, A. STAHN, AND W. URBAN, NBS Technical Note No. 1321 (1988).
11. L. R. BROWN AND R. A. TOTH, *J. Opt. Soc. Amer. B* **2**, 842-856 (1985).
12. D. E. JENNINGS AND J. W. BRAULT, *J. Mol. Spectrosc.* **102**, 265-272 (1983).
13. G. A. THOMPSON, A. G. MAKI, WM. B. OLSON, AND A. WEBER, *J. Mol. Spectrosc.* **124**, 130-138 (1987).
14. G. GUELACHVILI AND K. NARAHARI RAO, "Handbook of Infrared Standards," Academic Press, San Diego, 1986.