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Laser-Pumped Rubidium Frequency Standards: New Analysis and Progress

Gaetano Mileti, Jinquan Deng, Fred L. Walls, *Senior Member, IEEE,* D. A. Jennings, and R. E. Drullinger

***Abstract*—We have achieved a stability of 3·10^{-13} $\tau^{-1/2}$ for 3 $< \tau <$ 30 s with a laser-pumped rubidium gas-cell frequency standard by reducing the effects due to noise in the microwave and laser sources. This result is one order of magnitude better than the best present performance of lamp-pumped devices.**

***Index Terms*— Laser optically pumping, Rb frequency standard.**

I. INTRODUCTION

THE DEVELOPMENTS of tunable laser diode sources have opened new prospects for atomic clocks. Monochromatic light sources have improved the performance of the existing frequency standards (such as cesium beam standards) and led to new types of standards (such as fountains and other standards based on laser cooling) [1].

In the field of passive gas-cell frequency standards, much research on the replacement of the discharge lamp with a laser diode has been reported during the last 15 years [2]–[5]. Interesting new physical phenomena have been observed and studied [6]–[10] and great improvements in performance have been predicted [11]. However, the failure to achieve significant progress in the frequency stability and the problem of procuring reliable laser diodes has damped the initial momentum.

Our main interest is to build a “super” local oscillator for the standards based on cold atoms or ions [12]. Our goal is to first reach $\sigma_y(\tau) \sim 1{\cdot}10^{-13}\ \tau^{-1/2}$ (with a buffer-gas cell) and then $\sigma_y(\tau) \sim 1{\cdot}10^{-14}\ \tau^{1/2}$ (with a wall-coated cell) [14]–[16]. However, our analysis of the sources of instabilities in such a clock also applies to the more industrial or application-oriented approach [13]. In fact, the problem of how laser frequency modulation (FM) and amplitude modulation (AM) noise affects clock stability is the same, whether at the 10^{-14} or at the 10^{-11} level [14], [15]. Similarly, estimating how microwave synthesizer phase modulation (PM) noise affects clock stability is as important for a “super” local oscillator as for a miniature low-cost standard [16]. There is only a difference in scaling.

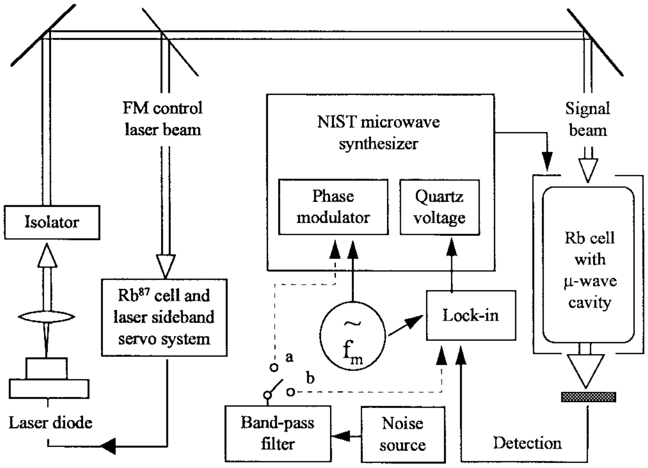

Fig. 1. Block diagram of the Rb clock. The role of the noise source is described in the text.

II. EXPERIMENTAL SETUP

We use the physics package of a commercial rubidium standard with the lamp and filter cell removed. The absorption cell contains isotopically pure Rb^{87} and has a total volume of 15 cm^3. One third of this volume is interrogated. A mixture of buffer gases provides efficient quenching and a low temperature coefficient. The microwave cavity (TE_{011} mode) has a Q of 100. See Fig. 1.

So far, we have considered three types of laser sources: broad-band solitary lasers, extended-cavity grating-feedback lasers (ECLD), and distributed Bragg reflector (DBR) lasers. The linewidths were 50 MHz, 100 kHz, and 2 MHz, respectively. The laser frequency is servo-controlled to a saturated absorption line of a separate evacuated Rb cell. Both the D_1 (795 nm) and D_2 (780 nm) transitions have been studied.

Our frequency synthesizer uses three low-noise quartz oscillators, at 5, 100, and 11.808 MHz. The 5-MHz oscillator is first multiplied by 2, and then by 10. This 100-MHz signal is used to phase lock the 100-MHz oscillator. The 100-MHz signal output of the second oscillator is phase-modulated (f_m, the modulation frequency, is about 300 Hz) and multiplied by 5. The 11.808-MHz output of the third oscillator, which is phase locked to an adjustable digital synthesizer, is subtracted from the 500 MHz. After being filtered and amplified, the 488-MHz signal is used to drive a step recovery diode. The 14th harmonic coincides with the “clock” transition frequency of rubidium and is injected in the microwave cavity. The microwave optical double resonance signal produced in the

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G. Mileti is with Observatoire Cantonal de Neuchâtel, CH-2000 Neuchâtel, Switzerland.

J. Deng, F. L. Walls, D. A. Jennings, and R. E. Drullinger are with the National Institute of Standards and Technology, Time & Frequency Division, Boulder, CO 80303 USA.

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TABLE 1
CURRENT NOISE @ 300 HZ (DC LEVEL: 3 μA) WITH THREE LASER DIODES AND LOCKING SCHEMES

Laser and locking type	Noise $[\mathrm{pA}/\sqrt{\mathrm{HZ}}]$ before Rb	Noise $[\mathrm{pA}/\sqrt{\mathrm{HZ}}]$ after Rb	Noise $[\mathrm{pA}/\sqrt{\mathrm{HZ}}]$ with cancellation
Solitary current mod. 70 kHz	2	30	3
ECLD piezo mod. 7 kHz	2	30	3
DBR sideband 12 MHz	1.2	1.2	1.2

physics package is then used to stabilize the 5-MHz oscillator. The PM noise of the 100-MHz signal after phase modulation is given by [16]

$$\begin{aligned} S_\Phi(f) &= 3.2 \cdot 10^{-14}\ \mathrm{rad}^2/\mathrm{Hz}, && f = 100\ \mathrm{Hz} \\ S_\Phi(f) &= 2 \cdot 10^{-14}\ \mathrm{rad}^2/\mathrm{Hz}, && f = 300\ \mathrm{Hz} \\ S_\Phi(f) &= 1.2 \cdot 10^{-14}\ \mathrm{rad}^2/\mathrm{Hz}, && f = 600\ \mathrm{Hz} \\ S_\Phi(f) &= 1 \cdot 10^{-14}\ \mathrm{rad}^2/\mathrm{Hz}, && 1\ \mathrm{kHz} < f < 1\ \mathrm{MHz} \\ S_\Phi(f) &< 5 \cdot 10^{-15}\ \mathrm{rad}^2/\mathrm{Hz}, && f > 1\ \mathrm{MHz}. \end{aligned} \tag{1}$$

III. ANALYSIS OF THE INSTABILITY SOURCES

This section has four parts which describe our analysis of the major limitations for the short-term frequency stability in our laser-pumped Rb standard. Section III-A identifies three sources of noise added to the resonance signal. Section III-B concerns the "aliasing" effect of the microwave synthesizer PM noise. Section III-C analyzes the light shift, and Section III-D discusses other effects.

A. Noise in the Photocurrent

As mentioned in previous studies, the ultimate short-term frequency stability $\sigma_y(\tau)$ is directly proportional to the photocurrent noise added to the resonance signal [14], [17], [18]. This noise has three main origins: detector noise, laser AM and FM (or PM) noise, and microwave AM and PM noise. They are reviewed below.

1) Current Noise Produced by the Detection Circuit: We use a photodetector in a transimpedance circuit. The noise sources are: the detector, the feedback resistor, and the operational amplifier. Our typical dc photocurrent is 3 μA. The feedback resistor is 1 MΩ. With this configuration, the noise from the detection circuit is 0.6 pA/$\sqrt{\mathrm{Hz}}$ (at 300 Hz).

2) Current Noise Produced by the Laser: The photocurrent noise in typical operating conditions, with the three types of laser sources, is given in Table I [14], [15].

The intrinsic intensity noise (column 2) of all the laser sources is not significantly higher than the shot noise. However, the values measured after the laser beam has passed through the vapor (column 3) indicate that additional noise is present on the detection photocell. This noise, which can be one order of magnitude higher than the shot noise (with the ECLD and the solitary laser), is due to laser phase noise combined with the atomic absorption [19]. The result for the ECLD is anomalously large. We think this is the result of mechanical perturbations to the ECLD interacting with the limited bandwidth of the locking loop. As shown in the last column of Table I, passive noise cancellation is also possible [14]. The shot noise can thus be approached with all three laser systems (shot noise + detector noise = 1.2 pA/$\sqrt{\mathrm{Hz}}$).

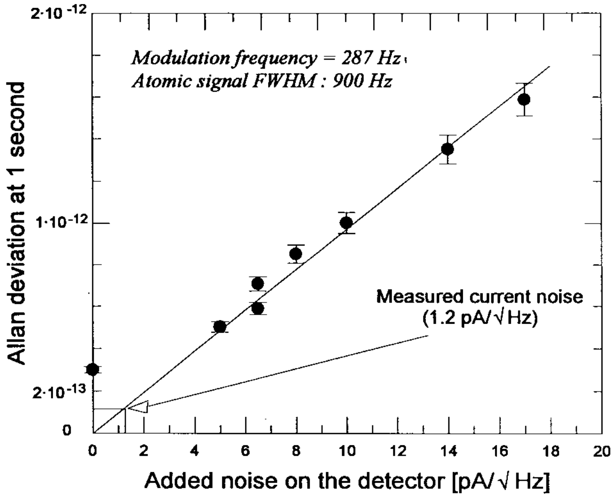

Fig. 2. $\sigma_y(1s)$ as a function of the photocurrent noise spectral density. Slope $= 9.7{\cdot}10^{-14}$/pA/$\sqrt{\mathrm{Hz}}$.

3) Current Noise Produced by the Microwave Field: In the presence of optical pumping, the microwave field induces a reduction of photocurrent. This absorption of light constitutes the double resonance signal for stabilizing the quartz oscillator. Unfortunately, it can also introduce additional noise. With a previous version of the synthesizer, the current noise increased from 1.5 (dc level: 5 μA) to 6 pA/$\sqrt{\mathrm{Hz}}$ (dc level: 3 μA) when the microwave radiation was present. The theoretical limit of $\sigma_y(\tau)$ was $6 \cdot 10^{-13}\ \tau^{-1/2}$, and we measured $8 \cdot 10^{-13}\ \tau^{-1/2}$ [16].

The clock stability was improved by introducing a phase-locked 11.808-MHz low-noise quartz oscillator (in the previous design the digital synthesizer was directly subtracted from the 500-MHz signal). After this modification, the photocurrent noise decreased to 1.2 pA/$\sqrt{\mathrm{Hz}}$ when the microwave radiation was present. Thus the contribution of the synthesizer to the photocurrent noise has been reduced to a negligible value.

4) Clock Stability Versus Current Noise: We have intentionally added noise centered on f_m (287 Hz) to the photocurrent signal (Fig. 1, switch on b). The resulting clock stability ($\sigma_y(1s)$) as a function of the added noise is shown in Fig. 2. The slope agrees with a previous estimate [7, eqs. (1) and (2)] $\sigma_y(\tau) \cong 1 \cdot 10^{-13} \cdot$ Noise $[\mathrm{pA}/\sqrt{\mathrm{Hz}}] \cdot \tau^{-1/2}$. With a noise of 1.2 pA/$\sqrt{\mathrm{Hz}}$, the limit of $\sigma_y(\tau)$ due to this noise is $1.2 \cdot 10^{-13} \cdot \tau^{-1/2}$.

B. "Aliasing" by the Local Oscillator PM Noise

As pointed out by Kramer [20], the PM noise at the even harmonics of the modulation frequency in the interrogating

TABLE II
LIMIT TO THE Rb CLOCK STABILITY ($\sigma_y(1s)$)
DUE TO THE PM NOISE OF THE SYNTHESIZER

Harmonic contribution	C_2 574 Hz	C_4 1148 Hz	C_4 to C_{42} 1-12 kHz	Total limit	With notch on C_2
Stability (σ_y(1 s))	$1 \cdot 10^{-13}$	$4 \cdot 10^{-13}$	$1 \cdot 10^{-14}$	$1 \cdot 10^{-13}$	$1 \cdot 10^{-14}$

These values are obtained using (2), the PM noise of (1), and the measured PM noise coefficients.

source, degrades the performance of passive atomic frequency standards. Various analyses on this "aliasing" problem have been published for standards operating either in the pulsed [21], [22] or continuous [23]–[25] mode.

We have experimentally evaluated the effect of the PM noise on the clock stability in our particular setup [16]. The total effect of the PM noise is

$$\sigma_y(\tau)_{\text{PM noise}} = \sqrt{\sum_{n=1}^{\infty} C_{2n}^2 S_\Phi(2nf_m \cdot \tau^{-1/2}} \qquad (2)$$

where S_Φ is spectral density of PM noise and C_{2n} are the phase noise coefficients. With the setup described in Fig. 1 (switch on position a) we added narrow-band PM noise centered on the different harmonics of f_m and measured $\sigma_y(\tau)$ as a function of the PM noise. Thus, we could evaluate the phase noise coefficients and, with the PM noise given by (1), determine the limit imposed by the microwave synthesizer. The results are summarized in Table II. The total limit on the short-term stability was $1 \cdot 10^{-13}\ \tau^{-1/2}$. It could be reduced by one order of magnitude with a notch filter on the second harmonic.

C. Light Shift Effects

Different authors have reported experimental and theoretical studies on light shift in laser-pumped rubidium frequency standards [6]–[10], [14], [15]. These studies help in estimating the effect of light shift on the clock stability, but an accurate evaluation of its contribution to the overall clock instability is still lacking. To our knowledge, only one study has directly measured the effect of light shift on the medium-term stability of a laser-pumped rubidium standard [26]. The main reason is that the two effects presented in the previous paragraph (A and B) were dominant. Since in our clock these two effects have been reduced, it is useful to reanalyze the light shift more carefully. We present our measurements and propose a new method for evaluating the effect of light shift.

The light shift coefficients near the zero-light-shift frequency ($\nu_{ls} = 0$), in our experimental setup, are given by (3) [14], [15]. In both cases, the laser was tuned so that the $F = 2$ hyperfine level of the ground state was depopulated. In (3),

$$\begin{aligned} D_1&: \quad \frac{\Delta\nu_{\text{clock}}}{\nu_{\text{clock}} \cdot \Delta\nu_{\text{laser}}^0 \cdot \Delta I_{\text{laser}}} \approx \frac{1 \cdot 10^{-14}}{\text{kHz} \cdot \mu\text{A}} \\ D_2&: \quad \frac{\Delta\nu_{\text{clock}}}{\nu_{\text{clock}} \cdot \Delta\nu_{\text{laser}}^0 \cdot \Delta I_{\text{laser}}} \approx \frac{2 \cdot 10^{-14}}{\text{kHz} \cdot \mu\text{A}} \end{aligned} \qquad (3)$$

where $\Delta\nu_{\text{laser}}^0$ is the laser detuning from $\nu_{ls} = 0$. Slightly different results are obtained in a different geometry or with different buffer gas conditions.

1) Medium- and Long-Term Stability: With (3), the requirements on the laser frequency stability and accuracy can be determined. We have not addressed this problem yet.

2) Short-Term Stability: As shown in Table I, the laser intensity noise (δI_{laser}) in the spectral domain around f_m is of the order of 1–3 pA/$\sqrt{\text{Hz}}$. Thus, if we suppose that the laser detuning ($\Delta\nu_{\text{laser}}^0$) is equal to or less than 50 MHz [15], the effect of δI_{laser} through the light shift is of the order of 1 to $3 \cdot 10^{-15}$. It is therefore negligible at present. The laser frequency noise ($\delta\nu_{\text{laser}}$) strongly depends on the type of laser and locking system. According to previously reported measurements [28], the spectral density of laser frequency noise is typically 5 kHz/$\sqrt{\text{Hz}}$. Thus, with a dc level of 2–3 μA and (3), we obtain

$$D_{1-2}: \quad \delta\nu_{\text{laser}} \approx 5\ \text{kHz} \rightarrow \frac{\delta\nu_{\text{clock}}}{\nu_{\text{clock}}} \approx 2 \cdot 10^{-13}. \qquad (4)$$

This simple estimate shows that the effect of laser frequency noise (through the light shift) on the clock short-term stability is not negligible at the 10^{-13} level. It is therefore necessary to evaluate more accurately this contribution to the clock instability.

3) Effect of Laser Frequency Noise on the Stability: We propose the following measurement to determine the effect of $\delta\nu_{\text{laser}}$ on the clock short-term stability. This method is similar to the method used to evaluate the effect of the photodetector noise (A) and the microwave PM noise (B). It consists of adding frequency noise to the laser beam and measuring the clock stability as a function of the added noise. Then, by measuring the intrinsic laser frequency noise, we can calculate the overall effect. Two different techniques can be used to add noise on the laser frequency. The first technique consists of adding calibrated current noise on the current driver of the laser. The second technique consists of using an AOM and adding noise on the driving rf signal. Unfortunately, we have not performed either of these measurements yet.

4) Eliminating the Light Shift Coefficient: Zero-light-shift coefficient can be obtained for the Rb^{87} D_1 transition, by fine adjustment of the buffer gas pressure [15]. In this case, the effect of laser frequency and intensity would be greatly reduced.

D. Other Effects

Other important effects, related to the microwave frequency stabilization loop, degrade the frequency stability of the standard [28]. In particular, significant AM noise is present in our local oscillator signal. We estimated that its component at the modulation frequency produces a shift of the clock frequency

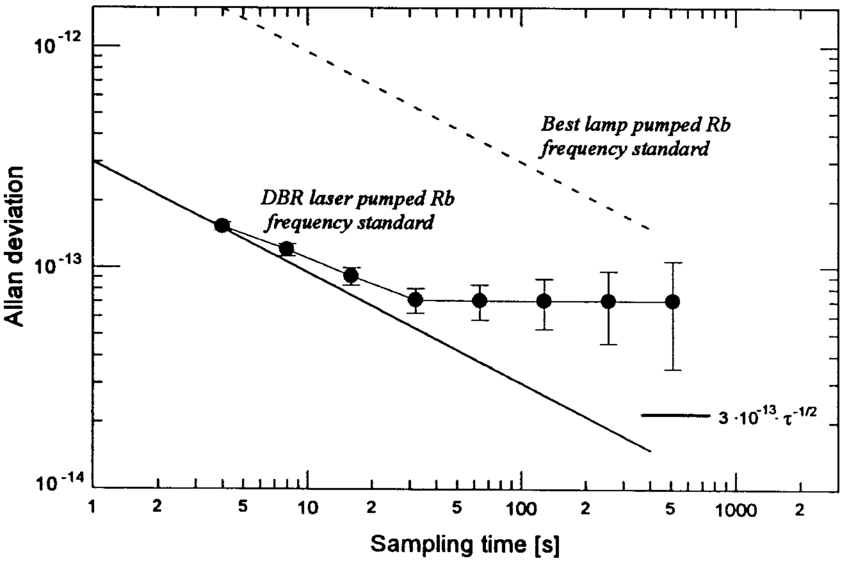

Fig. 3. Short-term stability of the Rb clock of Fig. 1.

of approximately $1 \cdot 10^{-11}$. More effort is needed to analyze this effect.

IV. FREQUENCY STABILITY MEASUREMENTS

According to the analysis of the previous section, the total limit for our laser-pumped Rb standard is

$$\begin{aligned}(\sigma_y^{\text{total}}(\tau))^2 &\approx (\sigma_y^{\text{I noise}}(\tau))^2 + (\sigma_y^{\text{PM noise}}(\tau))^2 + (\sigma_y^{ls}(\tau))^2\\ \Rightarrow \sigma_y^{\text{total}}(\tau) &\approx \sqrt{1.2^2+1^2+2^2}\cdot 10^{-13}\cdot\tau^{-1/2}\\ &\approx 2.5\cdot 10^{-13}\cdot\tau^{-1/2}.\end{aligned} \tag{5}$$

We have measured the stability under the following experimental conditions. A DBR laser was used to optically pump the rubidium vapor. It was locked to the $5S_{1/2}, F = 2 \rightarrow 5P_{3/2}, F'' = 3$ and $F' = 2$ cross-over transition at 780 nm. The laser frequency was about 20 MHz higher than $\nu_{\text{LS}=0}$. The total light shift was $1 \cdot 10^{-9}$. The modulation frequency of the local oscillator was 287 Hz. The results are shown in Fig. 3.

$\sigma_y(\tau)$ reaches $1 \cdot 10^{-13}$ after less than 10 s, which corresponds to a white frequency component of $3 \cdot 10^{-13} \cdot \tau^{-1/2}$. A flicker floor of $7 \cdot 10^{-14}$ is then reached, and the stability does not decrease further. This result corresponds to our prediction [(5)]. The origin of the relatively high flicker floor is not yet understood. We think that it is related to medium- and long-term laser beam intensity, frequency, and position fluctuations. This is the best short-term stability ever measured with passive, gas-cell frequency standards. For comparison, the best performance of lamp pumped standards is also shown in Fig. 3.

V. SUMMARY

We have built a laser-pumped gas-cell rubidium frequency standard which has demonstrated a short-term frequency stability of $3 \cdot 10^{-13}\ \tau^{-1/2}$ for $3 < \tau < 30$ s. The major limitations on frequency stability are the photocurrent noise on the detector, the PM noise in the microwave synthesizer, and the combined effect on laser frequency noise with light shift.

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Gaetano Mileti was born in St-Aubin, Switzerland, in 1968. He received the Engineering Degree in physics from the Swiss Federal Institute of Technology, Lausanne, in 1990 and the Ph.D. degree in physics from Neuchâtel University, Neuchâtel, Switzerland.

He has been with the Cantonal Observatory of Neuchâtel, Neuchâtel, Switzerland, since 1991. He was engaged in research on atomic frequency standards and on the applications of stabilized laser diodes. He took part in the development of lamp-pumped Rb gas-cell frequency standards for industrial and space applications and performed original research on laser-pumped Rb standards. From 1995 to 1997, he was a Guest Scientist in the Time and Frequency Division of the National Institute of Standards and Technology, Boulder, CO, on the devlopment of a super local oscillator. Since 1997, he has been involved in LIDAR research at the Observatory of Neuchâtel.

Jinquan Deng was born in Zhuzhou, China, in 1959. He received the B.S. degree in physics from Hunan Normal University, Changsha, China, in 1982, the M.E. degree in radio physics from the Institute of Electronics, the Chinese Academy of Sciences, Beijing, China, in 1985, and the Ph.D. degree in quantum electronics from the Wuhan Institute of Physics, the Chinese Academy of Sciences, Wuhan, China, in 1991.

He has been with the Laboratory of Atomic Frequency Standards, Wuhan Institute of Physics, the chinese Academy of Sciences, Wuhan, since 1985. He has engaged in the research of Rb maser and the development of Rb gas-cell frequency standards. Since 1995, he has been a Guest Scientist in the Time and Frequency Division, National Institute of Standards and Technology, Boulder, CO, working on laser-pumped Rb gas-cell frequency standards.

Fred L. Walls (A'93–SM'94) was born in Portland, OR, on October 29, 1940. He received the B.S., M.S., and Ph.D. degrees in physics from the University of Washington, Seattle, in 1962, 1964, and 1970, respectively. His Ph.D. dissertation was on the development of long-term storage and nondestructive detection techniques for electrons stored in Penning traps and the first measurements of the anomalous magnetic (g-2) moment of low-energy electrons.

From 1970 to 1973, he was a Post-Doctoral Fellow at the Joint Institute for Laboratory Astrophysics, Boulder, CO. This work focused on developing techniques for long-term storage and nondestructive detection of fragile atomic ions stored in Penning traps for low-energy collision studies. Since 1973, he has been a Staff Member of the Time and Frequency Division of the National Institute of Standards and Technology, formerly the National Bureau of Standards, Boulder, CO. He is presently Leader of the Phase Noise Measurement Group and is engaged in research and development of ultrastable clocks, crystal-controlled oscillators with improved short- and long-term stability, low-noise microwave oscillators, frequency synthesis from RF to infrared, low-noise frequency stability measurement systems, and accurate phase and amplitude noise metrology. He has published more than 120 scientific papers and holds five patents.

Dr. Walls is a member of the American Physical Society, a member of the Technical Program Committee of the IEEE Frequency Control Symposium, and a member of the Scientific Committee of the European Time and Frequency Forum. He received the 1995 European "Time and Frequency" award from the Societé Francaise des Microtechniques et de Chromometrie "for outstanding work in ion storage physics, design and development of passive hydrogen masers, measurements of phase noise in passive resonators, very low noise electronics and phase noise metrology." He is the recipient of the 1995 IEEE Rabi award for "major contributions to the characterization of noise and other instabilities of local oscillators and their effects on atomic frequency standards." He has also received three silver medals from the U.S. Department of Commerce for fundamental advances in high-resolution spectroscopy and frequency standards, the development of passive hydrogen masers, and the development and application of state-of-the-art standards and methods for spectal purity measurements in electronic systems.

D. A. Jennings, photograph and biography not available at the time of publication.

R. E. Drullinger, photograph and biography not available at the time of publication.