A History of the Rubidium Frequency Standard

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***Abstract*--This paper is a history of the rubidium gas cell atomic frequency standard, by far the most widely deployed type of atomic clock. Since the early 1960's, rubidium frequency standards (RFS) have offered an attractive combination of practicality and performance that spans a range of applications from low-cost commercial devices for telecommunications timing, ruggedized tactical units for military use, and high stability, high reliability space clocks for global navigation systems. The paper describes their physical basis, the early scientific work that created them, and their subsequent product development and widespread commercialization from the perspective of an early contributor to this field. It emphasizes the author's experiences at several organizations that continue to make RFS devices, and similar new atomic clock technology, smaller, better, and cheaper. That work was carried out in the U.S. and elsewhere by a series of organizations and people following several distinct timelines and heritages. The first complete RFS was designed in the late 1950's at ITT in Nutley, NJ by Dr. Maurice Arditi with Dr. Thomas Carver of Princeton, and that organization is now the largest user of space Rb clocks for their GPS navigation payloads. The first commercial RFS appeared in the early 1960's from General Technology and Space Technology Laboratories. Some of the first commercial RFS were built circa 1962 by Varian Associates in Palo Alto, CA, and that technological legacy continues today.**

***Index Terms*--Atomic clock, history, rubidium frequency standard.**

I. INTRODUCTION

THE rubidium gas cell frequency standard has, over the last 60 years or so, become the dominant type of atomic clock because of its combination of practicality and good performance. While its design fundamentals have changed little over that time period, there has been remarkable progress in adapting it to a wide range of demanding space-qualified requirements, rugged military applications and low cost commercial telecom usage. This paper will review some of that history.

A. *Atomic Clocks*

An atomic clock is a device that utilizes an atomic resonance to produce a highly-stable frequency suitable as a frequency reference and/or for precise timekeeping.

The rubidium gas cell atomic frequency standard (RFS or "Rb oscillator"[1]) is, by far, the most commonly-used form of atomic clock. Its scientific basis began in the 1950's and its commercialization was well underway by the early 1960's, first as a laboratory instrument, then primarily for tactical military communications and now in widespread use by the telecom industry. Atomic clocks play a critical role in global navigation satellite systems (GNSS). General atomic clock references herein are [1] through [5].

B. *Requirements for an Atomic Frequency Standard*

The fundamental basis of an atomic frequency standard (AFS) is utilization of an atomic resonance that is, in principle, an inherent and invariant natural property. In practice, to implement an AFS, one must devise an apparatus that allows one to observe an atomic resonance in a detectable manner and with minimal external disturbance.

The requirements for implementing an atomic frequency standard are means to confine the atoms, prepare them into a particular state and then to interrogate them to probe their resonant frequency[2] [9].

In the case of the common RFS, Rb atoms are confined in an inert buffer gas in a small glass "cell", they are prepared in a particular hyperfine atomic state by a process called optical pumping using an Rb spectral lamp, and their atomic resonance is interrogated by means of RF energy applied to a microwave cavity. The Rb resonance at about 6.835 GHz is detected optically by a photodiode that senses the light transmitted through the absorption cell.

C. *Why Use An Atomic Clock?*

Relatively few atomic clocks are used as frequency standards per se but rather as sources of precise time. Maintaining time to the microsecond level (a rather large error for a fast data stream) over a few days requires a frequency source error well below the $1\text{x}10^{-11}$ level, which is a demanding requirement for an ovenized quartz crystal oscillator[3]. Thus an RFS can be the most practical choice. Common RFS timing applications include cellular telecommunications, geophysical data logging, GPS fast acquisition/robustness and frequency hopping radios. High performance Rb clocks have become the device of choice onboard GPS satellites.

D. *Previous RFS Historical Reviews*

The first historical review of atomic frequency standards by Arthur McCoubrey appeared in 1966 [1]. That was quite early in the history of rubidium frequency standards, and it contained a brief description of their physical principles (which were fully in place by then), their performance, and several examples of RFS products from General Technology and Varian. McCoubrey followed that survey by another one 30 years later at the 50th anniversary of the Frequency Control Symposium in 1996 [16]. Roger Beehler wrote a historical review of

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[1] The term "Rb oscillator" is a misnomer because an RFS is a passive AFS. The Rb physics package is a passive discriminator not an active oscillator. Nevertheless, the term is reasonably descriptive and widely used.

[2] As I recall, these fundamental requirements were first elucidated by Helmut Hellwig in various papers and tutorials, including [2].

[3] For example, the LTE timing requirement is ±1.5 μs.

atomic frequency standards in 1967 that contains an excellent summary of the development of practical RFS devices [7]. He followed that with a progress report on commercial rubidium (and other) frequency standards written in 1973 [10]. In 1972, Norman F. Ramsey published his first history of atomic clocks [8], which was followed by several others over the succeeding years [12], [15], [19]. Reference [5] contains a very brief RFS history. This paper updates those previous reviews, covering only the passive rubidium gas cell atomic frequency standard and the closely-related CPT and CSAC devices[4].

II. PHYSICS

The history of rubidium frequency standards began as a practical application of scientific research conducted mainly in the U.S. following World War II.

A. Rubidium as the Atom of Choice

37
Rb
Rubidium
85.4678

Rubidium is an alkali atom, one having a single electron in its outer shell, and it is the energy state of that valance electron that is used as an atomic frequency reference.

In particular, the so-called hyperfine resonance that represents the small energy difference between the two outer electron spin states is well-suited for that purpose, having a frequency in the microwave range. Rb is uniquely suited for this purpose because, as explained below, it exists as two common isotopes, Rb-85 and Rb-87, which facilitate its state selection by optical pumping.

See Reference [234] for information about the physical properties of Rb-87. References herein to general RFS theory are [37] through [45].

B. Underlying Physical Research

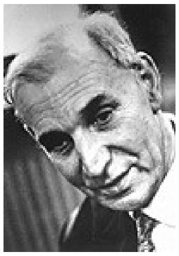
The physics of atomic frequency standards is based on underlying research, some conducted by Nobel laureates studying the fundamental properties of atoms, whose apparatus evolved into practical devices for frequency control. Much of that evolution can be followed in papers presented at the Frequency Control Symposium (FCS) during the 1950's. Atomic clocks are a prime example of scientific research leading to applied technology. References herein to early RFS scientific papers are [23] through [36].

C. The First Atomic Clocks

The first type of atomic clock still being made today, the cesium beam tube device, was based on the early scientific research by Stern and Gerlach and I. I. Rabi [14].

For rubidium gas cell devices, the seminal concepts include: optical pumping (A. Kastler, Paris, 1950[5], [6]), resonance line narrowing by a buffer gas (R. H. Dicke, Princeton Univ., 1953[6], [17]), optical detection (H. G. Dehmelt, Univ. Washington, 1957), hyperfine filtration (T. R. Carver and C. O. Alley, Princeton Univ., 1958)[7], and optical detection, isotopic filtration, buffer gas effects, TC, light shifts, etc. (P. L. Bender, E. C. Beaty, NBS and A. R. Chi, NRL, 1958)[8]. Photographs of some of these key contributors to early RFS technology are shown in Fig. 1.

Isidor I. Rabi (1898-1988)
Father of the atomic clock
Photo Credit: Wikipedia.



Alfred Kastler (1902-1984)
Optical Pumping
Photo Credit: Wikipedia.

Robert H. Dicke (1916-1997)
Buffer Gas Linewidth Reduction.
etc. Photo Credit: Wikipedia.

Thomas R. Carver (1929-1981)
Isotopic Hyperfine Filtration. etc.
Photo Credit: Princeton Univ.

Carroll O. Alley (1927-2016)
Isotopic Hyperfine Filtration
Photo Credit: Univ. of Maryland.

Maurice Arditi (1913-)
Complete RFS
Photo Credit: IEEE.

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[4] This document is "a history" not "the history" of the rubidium frequency standard. I am not a historian but rather a participant in that endeavor, whose complete story would require a broader perspective.

[5] Alfred Kastler (1902-1984) invented the method of optical pumping to excite the energy levels of atoms in 1950, which is the basis of the optical state selection used in most Rb frequency standards. He received the Nobel Prize in Physics for this work in 1966.

[6] Robert Dicke (1916-1997) predicted and experimentally showed that collisions that restrict the long-range motions of radiating atoms in a gas can suppress Doppler broadening, which is the basis for gas cell atomic frequency standards. [28]. He invented the lock-in amplifier that uses synchronous demodulation to detect weak signals, a process that is used in all passive atomic frequency standards, and was a founder of Princeton Applied Research (later, in 1977, an EG&G company), the first manufacturer of those devices in 1962. He also invented the radiometer and just missed discovering the cosmic microwave background radiation.

[7] I visited Dr. Alley at his home near the University of Maryland in September 2008, and asked him about the invention of the rubidium frequency standard. He did not give a definitive answer, and it seems that a number of people in several groups brought it all together in the late 1950's. The scientists moved on to other things and the engineers took over from there.

[8] Robert Dicke led the group at Princeton. Tom Carver was an instructor starting in 1954 and became a full professor in 1967; he consulted with ITT (e.g., Maurice Arditi). Carroll Alley was a grad student there when the seminal Rb groundwork was done.

Hans G. Dehmelt (1922-2017)
Optical Detection
Photo Credit: Wikipedia.

Earl C. Beaty (1930-2018)
Buffer Gasses,
Isotopic Filtration, etc.
Photo Credit: JILA/Univ. CO.

A. R. Chi (1920-1982)
Buffer Gasses,
Isotopic Filtration, etc.
Photo Credit: IEEE.

Peter L. Bender (1930-)
Buffer Gasses,
Isotopic Filtration, etc.
Photo Credit: JILA/Univ. CO.

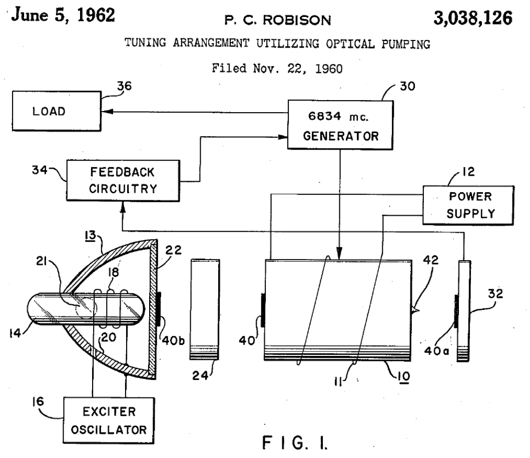
Fig. 1. Some Key Early Contributors to RFS Technology. These investigators established the scientific basis for rubidium frequency standards.

Rabi, Dehmelt and Kastler were Nobel laureates. Dicke probably should have shared one for discovery of the cosmic background radiation (CMB).

Many scientists and engineers contributed to the development of the rubidium gas cell atomic frequency standard (RFS), and it is not possible to attribute its invention to any single person or organization[9, 10, 11, 12] [13].

The first suggestion for building an ‘atomic clock” is generally credited to a January 1945 lecture by I. I. Rabi of Columbia who won the 1944 Nobel Prize for his work on nuclear magnetic resonance. In 1949-1950, F. Bitter of MIT and A. Kastler in Paris discovered the technique of optical pumping, for which Kastler received the Nobel Prize in 1966. That was followed by the 1953 suggestion by R.H Dicke of Princeton that the Doppler broadening of atomic resonance lines could be reduced by a buffer gas, the method of optical detection by H.G. Dehmelt in 1957 (recipient of the 1989 Nobel Prize), and the use of isotopic filtration in 1958 by T. R. Carver and C. O Alley of Princeton. Meanwhile, P. L. Bender, E. C. Beaty of NBS and A. R. Chi of NRL[13] were studying buffer gas and light shift effects. By that time these and other investigators had established the scientific basis of the rubidium gas cell atomic frequency standard that continues to be utilized today. That scientific work was quickly utilized to build prototype Rb frequency standards, and by the early 1960’s commercial units became available.

Several patents from this era describe arrangements and show block diagrams that are little different from RFS designs today (see Figs 2 and 3)[14]. References herein for RFS patents are [235] through [322][15].



F I G. I.

Fig. 2. Early Rb Physics Package. This figure from a circa 1960 Space Technology Laboratory patent shows all the ingredients of a modern RFS physics package: Rb lamp 14 and exciter 16, Rb-85 filter cell 24, Rb-87 absorption cell 10, C-Field coil 11 and photodetector 32. It mentions applying the microwave excitation with a cavity per Dicke’s 2,940,050 patent.

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[9] A case can be made that the first serious effort to develop an actual gas cell atomic frequency standard was undertaken by Maurice Arditi at the ITT Federal Telecommunications Laboratories in Nutley, NJ where he worked until 1965. Dr. Arditi was the right person at the right place at the right time to do that. He was an ITT employee in France who came to the U.S. shortly before World War II with degrees in both engineering and physics. ITT was then, and remains today (as Harris) at the same location, in the avionics business, and was quite close to Princeton where Robert Dicke’s physics group (e.g., Tom Carver) had laid the theoretical and experimental groundwork for this technology. Arditi began with sodium, mainly because its lower hyperfine frequency made the microwave hardware easier. He then moved on to cesium and then rubidium. One supposes (but I was unable to confirm) that the final preference for Rb was (as it remains today) because of isotopic filtration).

[10] Dr. Alley’s Wikipedia page includes the following: “His PhD dissertation developed new methods of detecting the ground state hyperfine transition in optically-pumped rubidium vapor for the type of atomic clock invented by Princeton professors Robert Henry Dicke—Alley’s thesis advisor—and Thomas R. Carver. This type of atomic clock was later used in the U.S. Global Positioning System and the European Union’s Galileo Global Positioning System.”

[11] I find it ironic that ITT in Nutley, NJ, now part of Harris and the largest user of high performance space Rb clocks, and one of the main spawning grounds of that technology, announced in a 1958 news release a “lightweight atomic clock” as an “aid to space navigation in the future” but then, in 1965, declared “Dr. Arditi’s atomic clock research has not been considered by ITT as worthy of continued financial support”. He was clearly far ahead of his time.

[12] In [13], on p. 396, Dr. Alley says “… the rubidium vapor gas cell type using optical pumping and optical detection, which was proposed by R.H. Dicke and was developed initially at Princeton, notably by T.R. Carver, with contributions by others, including the present writer…”.

[13] Andrew R. Chi joined NRL in 1957 and collaborated with physicists from NBS in developing gas cell frequency standards using optical pumping techniques. He and his colleagues were the first to measure the Rb-87 hyperfine frequency, and the first to measure the pressure shift and TC of various buffer gasses in a gas cell frequency standard.

[14] See U.S. Patent Nos. 2,836,722, 2,882,493, 2,884,524, and 2,927,278.

[15] While relatively few of these patents are referenced in the text, they help to show the evolution of RFS technology and the persons and organizations involved.

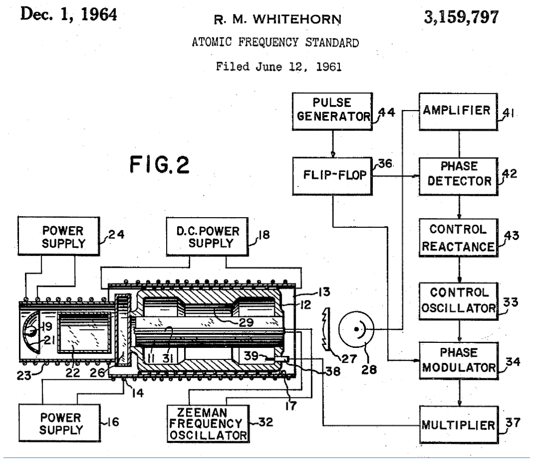

Fig. 3. Early RFS Block Diagram. This figure from a circa 1960 Varian patent shows all the ingredients of a modern RFS block diagram: Rb lamp 19 and oven assembly with isotopic filter 22, absorption cell 11 / microwave cavity 12 assembly, C-field coil 17, magnetic shield 13, photodetector 28, preamplifier, synchronous detector 42, VCXO 43 & 33, phase modulator 34, and RF multiplier chain 37-39. Arditi shows a similar block diagram in an ITT patent 3,174,114 filed in 1959 for a Na-based gas cell clock. Varian patent 3,363,193 filed in 1966 shows a completely modern RFS block diagram that includes a synthesizer scheme.

III. TECHNOLOGY

Let us now examine some of the technology used in rubidium atomic frequency standards and the way it has evolved.

A. The First Rubidium Frequency Standards

The burst of intensive work during the late 1950's (e.g., see the 1958 FCS Proceedings) makes it difficult to ascribe the first practical RFS to a single individual or group. Nevertheless, it seems to me that one can credit that to Maurice Arditi of ITT Laboratories and Thomas Carver of Princeton University (a member of Robert Dicke's group)[16, 17]. The January 1963 *Proc. IEEE* paper by M. Arditi and T. R. Carver [53] is a good overall reference to their work. One can also cite similar work by Carpenter, Packard & Swartz and others. Much of that work was described in papers at the 1958 Frequency Control Symposium. Prototype RFS units soon followed in the early 1960's as reported by Arditi & Carver, Carpenter, Packard & Swartz and others. Commercial units became available from Varian and General Technology soon thereafter. References herein to early RFS R&D are [46] through [58].

A basic block diagram of an RFS is shown in Fig.4. This block diagram applies to any type of passive atomic clock wherein a crystal oscillator is locked to an atomic reference.

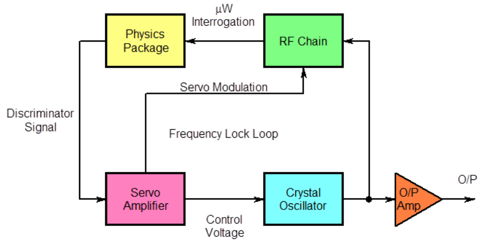

Fig. 4. RFS Block Diagram. This block diagram applies to any passive atomic frequency standard.

A more detailed diagram of a classic lamp pumped Rb physics package with separate filter and absorption cells is shown in Fig. 5[18]. This arrangement is still in use today (e.g., in the Excelitas GPS RAFS).

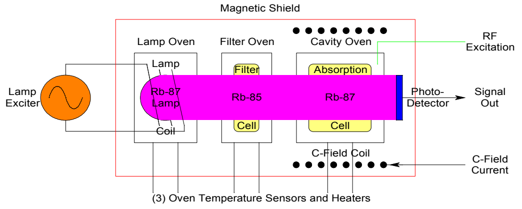

Fig. 5. Rb Physics Package. This Rb physics package diagram shows a separate isotopic filter cell.

B. Isotopic Filtration

The key property of rubidium that makes it uniquely suited for an optically pumped gas cell atomic frequency standard is the fortuitous overlap in the hyperfine optical spectrum between the Rb-85 and Rb-87 isotopes that allows increased optical pumping efficiency by isotopic filtration as shown in Fig. 6.

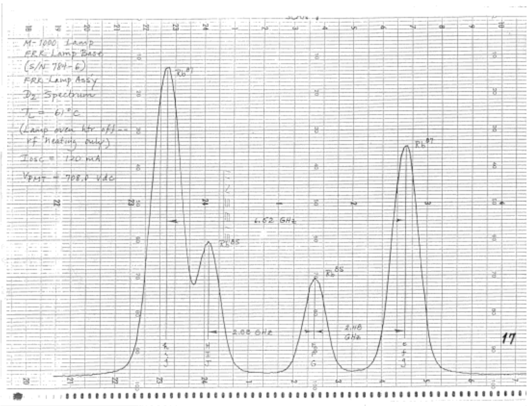

Fig. 6. Rb Lamp D_2 Line Optical Spectrum. This spectrum is for a mixed-isotope Rb lamp. The Rb-87 lines are stronger and they are separated by the 6.835 GHz hyperfine frequency. Notice the overlap between the two Rb isotopes for the lower hyperfine level. Photo Credit: Efratom.

C. Discrete and Integrated Filter Cells

An RFS can use either a separate Rb-85 filter cell or an integrated resonance cell containing both Rb-87 and Rb-85 (likely as natural Rb) [275]. Both arrangements work well, but

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[16] I contacted Dr. Arditi via e-mail in 2009 thanks to detective work by Tony Lomnicki at ITT/Exelis, who traced him down in France via his ITT retirement records. Maurice Arditi was born on March 1, 1913 in Paris, and was still living there at age 96 at that time, when he kindly shared some stories about his work on Rb clocks.

[17] I had the privilege sometime around 2005 to examine several of Dr. Arditi's notebooks in the ITT Nutley, NJ library. One could feel him struggling to do something that had never been done before. I recall somewhat the same experience at General Radio when Herb Stratemeyer and I searched for the Rb resonance with our experimental apparatus, and we, of course, knew where to look thanks to Arditi's and others work.

[18] In early RFS, the physics package was often call the "optical assembly" or "optical microwave assembly" (OMA, but not a German grandmother). "Physics package" has nuclear weapons implications, but that's another story.

the discrete filter cell allows better absorption cell homogeneity, high S/N, ease of light shift nulling, lower sensitivity to microwave excitation power. Two examples of Rb resonance cells are shown in Fig. 7.

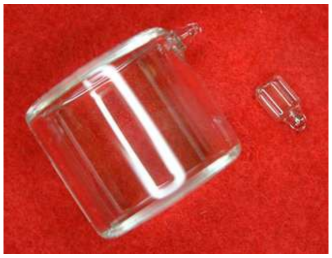

Fig. 7. Rb Resonance Cells. Left: Symmetricom 8130A resonance cell 1'' diameter x 1" long. Right: Symmetricom X72 resonance cell about 0.3" long. Photo Credit: Symmetricom.

D. Buffer Gas

Absorption/resonance cell buffer gas is used to narrow the resonance line by confining the Rb atoms to reduce wall collisions and Doppler shift, as shown in Fig. 8[19]. Nitrogen is universally used to quench re-radiated pumping light. Various buffer gas species have different pressure shift[20] and temperature coefficients thereby determining cell frequency offset and TC. These buffer gas frequency shifts make the RFS a "secondary" (albeit stable) standard of frequency. Cell envelope glass is selected for low microwave loss and low helium permeation[21]. Wall coatings are seldom used instead of buffer gas in an RFS[22].

E. Rb Lamps

An electrodeless Rb discharge lamp (see Fig. 9) is a remarkably effective and low noise optical pumping source.

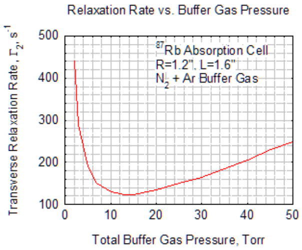

Fig. 8. Buffer Gas Linewidth Reduction. A lower relaxation rate narrows the resonance line and improves its Q. There is an optimum buffer gas pressure as a tradeoff between confinement and collisional broadening.

Using the same Rb-87 isotope as the absorption cell, it is automatically at the right nominal wavelength, and its plasma broadens its spectrum sufficiently so that it is stably insensitive to small variations in operating conditions. The lamp contributes negligible noise above that of the shot noise intrinsic to the optical detection process.

Fig. 9. Rb Lamp. This is a GPS RAFS lamp in its screw-in holder. Photo Credit: PerkinElmer.

The classic problem with Rb lamps has been life and reliability due to rubidium depletion as the excess Rb diffuses into the glass envelope. There is a tradeoff between having sufficient Rb fill for satisfactory life and too much excess Rb that increases lamp noise. That problem was solved by Tom Lynch at EG&G circa 1980 when he invented a way to precisely measure lamp Rb fill using a differential scanning calorimeter (DSC) to measure the amount of heat energy required to melt it, as shown in Fig. 10[23], [115]. References herein for Rb lamps are [111] through [117].

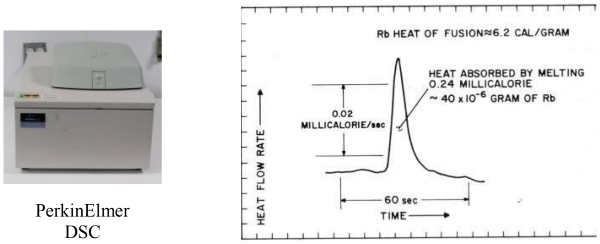

Fig. 10. Rb Lamp Calorimeter Record. The area under the Rb lamp calorimeter record indicates the amount of heat energy required to melt it, which, by knowing the Rb heat of fusion, determines its mass. Photo Credit: PerkinElmer, Plot Credit: EG&G.

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[19] Buffer gases are commonly used to reduce the linewidth of microwave transitions in alkali atoms. The lifetime of the atomic state determines the width and Q of the resonance. To improve the atomic Q, around 10 Torr of an inert gas such as Ne, Ar or N_2 is added to the cell. The alkali atoms collide frequently with the buffer gas and therefore diffuse slowly throughout the cell before they hit the wall. The atomic Q is increased to about 10^8, which results in a much better frequency stability than could be obtained with a pure Rb vapor alone.

[20] Pressure shift coefficients are positive for light gasses (e.g., He, Ne) and negative for heavy gasses (e.g., Kr, Xe). The pressure is usually measured at room temperature where the cell is filled and the frequency shift is measured at the cell operating temperature. The values are quite similar for both large and small, rubidium and cesium cells.

[21] Helium is highly permeable through most glass. Atmospheric He can diffuse into an absorpsion cell, changing its buffer gas mixture and raising its frequency. In subsequent space (vacuum) operation, the frequency can age lower. A copper cell with brazed sapphire windows and a pinchoff would have excellent cleaning, bakeout and sealing properties, and could also serve as a cavity/oven, but this has never been widely used (see U.S. Patent No. 6,215,366).

[22] A wall coated cell can have a narrow resonance line width but it also commonly has an unacceptably large temperature coefficient. A wall coated cell wthout buffer gas to confine the Rb vapor in a TE_{111} microwave cavity must have a septum to separate the two regions of opposite RF H field polarity.

[23] Zero in-orbit GPS RAFS Rb lamp failures have occurred since adopting DSC lamp screening. A somewhat similar but less severe issue regarding lamp Xe buffer gas fill was resolved more recently by non-destructively measuring the Xe buffer gas pressure by operating the lamp as an absorption cell and measuring its frequency offset.

F. Lamp and Cell Processing

Rb lamps and cells are processed on high vacuum systems like that shown in Fig. 11. The general procedure is to fabricate the glass envelopes and their tubulations, chemically clean them, attach them to a manifold on the vacuum system, bake out, plasma clean and pump down the empty lamps or cells, break an Rb ampoule inside the manifold and distill Rb into the lamps or cells, introduce the appropriate buffer gas at the correct pressure, pull the lamps or cells off the system, and finally shorten their tubulations[24, 25].

Fig. 11. Rb Lamp Processing. A manifold of Rb lamps attached to a high vacuum processing system. Photo Credit: EG&G.

G. Lamp Exciters

Rb lamp exciter circuits have been the subject of much development effort to assure reliable lamp starting and stable operation. These circuits require about ½ watt of RF power at around 100 MHz[26]. The Rb lamp is usually excited inside a series-tuned coil, and a power oscillator has been found to work better than a separate source and amplifier. Early RFS designs used vacuum tube lamp exciters, and today's rugged RF power transistors make these circuits very reliable. Starting requires developing a high resonant RF voltage across the coil[27, 28, 29, 30], while the lower-impedance lit lamp is driven mainly by the RF magnetic field. An operating Rb lamp in a cut-away physics package is shown in Fig. 12. A reference herein for lamp exciters is [118].

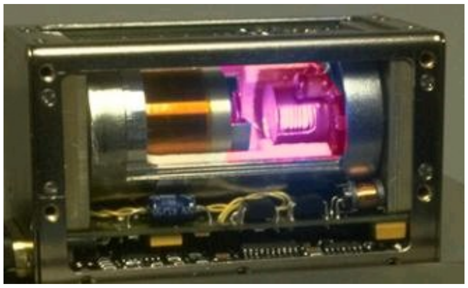

Fig. 12. Operating Rb Lamp in Cut-away Physics Package. Note the excitation coil that surrounds the lamp in its oven. Photo Credit: Temex Neuchatel Time.

H. Optical Filtration

An Rb lamp produces an output that contains spectral lines from both its Rb fill and its buffer gas (typically Xe), all of which contribute shot noise at the photodetector. An optical filter can be used to remove much of the unwanted light and thus improve the S/N ratio and short-term stability.

I. Pulsed Light

In principle, light shift could be avoided in an RFS by pulsing the pumping light and doing the interrogation in the dark. This technique has not, however, been widely used[31].

J. C-Field

A DC magnetic bias field or "C-Field" on the order of 50-250 mG is necessary to provide a magnetization axis and to separate the Zeeman lines so that the frequency lock servo can lock on to the central "field independent" line[32]. It can also be used to adjust the RFS frequency, but, for best stability, it is better to operate at a fixed minimum C-field and use another means (e.g., a synthesizer) for tuning [167]. It may be necessary to boost the C-field during lock acquisition to avoid lock-up on a Zeeman line.

By periodically commutating the C-field polarity it is possible to reduce RFS sensitivity to external DC magnetic fields [168][33, 34]. References herein for the RFS C-field are [167] and [168].

K. Magnetic Shielding

All RFS units require magnetic shielding to establish a region of uniform C-field in the physics package and to reduce their sensitivity to external magnetic field variations. Refer-

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[24] The ultra-high vacuum cell processing systems at EG&G/PerkinElmer/Excelitas originally came from General Radio/GenRad and thus date back to the mid-1960's, although some of their pumps, valves, gauges, etc. have, of course, been replaced.

[25] The need for ultra-high vacuum (say below 10^{-10} Torr) before lamps and cells are filled with Rb and buffer gas is debatable considering the finite purity of the buffer gas and glass out-gassing during tipoff. The most important thing is probably the condition of the glass envelope surface, and the chemical and ion bombardment processes used to clean it.

[26] It is important to shield this RF energy to avoid unwanted conducted and radiated emissions from the RFS.

[27] Cosmic radiation is thought to play a role in initial lamp ionization.

[28] Lamp starting after prolonged storage has been a concern but never an actual problem. Even if the rubidium forms a conductive film that inhibits starting, RF induction heating will clear it as long as the lamp exciter oscillates. Experience with GPS Rb clocks has shown that they start OK after decade-long in-orbit storage.

[29] A room full of Rb lamps can be lit with a single camera flash.

[30] Use of a radioactive buffer gas to initiate a plasma discharge was considered for Rb lamps at EG&G in Salem, MA, which had a licensed Kr-85 facility. But that was never tried, it being considered unnecessary and not worth the trouble. Bob Vessot alluded to using it to aid H-maser dissociator starting, but again it was probably never actually done.

[31] The most serious attempt at pulsed light operation of a conventional lamp-pumped RFS was probably that done by Tom English et al. at Efratom [113]. But the Rb lamp isotopic mix and Rb-85 filter cell recipes can do an excellent job of light shift suppression. Pulsed light is a more attractive possibility when a diode laser is used as the pumping source.

[32] The term "C-Field" apparently originated with a label on Rabi's NMR apparatus.

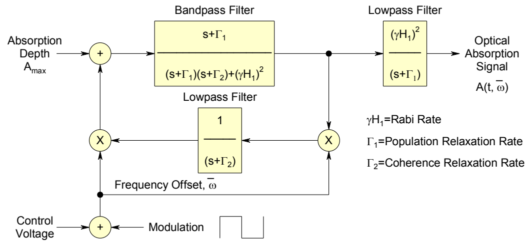
[33] Periodic reversal of the C-field has been used to reduce RFS magnetic sensitivity. The Collins AFS-81 used a Hall sensor to compensate for external magnetic fields.

[34] C-field commutation has been used by AccuBeat and by Stanford Research Systems in their PSR10 rubidium frequency standard. In the latter, clever digital signal processing avoids problems with interference and achieves a x25 reduction in external magnetic field sensitivity.

ences herein for RFS magnetic shielding are [169] through [173].

L. Rb Signal Modeling

The discriminator signal from an Rb physics package is well understood and can be accurately modeled using methods devised by R.P. Kenschaft at General Radio in 1969 [164] and later by Jim Camparo and Bernardo Jaduszliwer at the Aerospace Corporation[35]. The former devised the so-called Kenschaft model (see Fig. 13) and the latter a refined version of it[36, 37].



Block Diagram of Kenschaft Model of Rb Signal

One important application of the Kenschaft model was to analyze the response the response of an Rb physics package to servo upset such as can occur due to transient radiation [165].

R.P Kenschaft
Photo Credit: GR 1969 Picture Book.

Fig. 13. Kenschaft Model of Rb Signal.

References herein for Rb signal parameters are [160] through [163] and for the Kenschaft model are [164] through [166].

M. Lock Detection and Acquisition

It is important that there be an indication when an RFS frequency control loop is locked, and fortunately that quite easy to do by detecting the presence of the strong 2nd harmonic signal that exists only when the frequency of the applied interrogation RF is near the center of the resonance line and the fundamental signal is nulled by the servo loop[38].

Any passive AFS must employ some means to acquire lock-up on the atomic resonance. While that can happen by itself if the active frequency source is highly accurate, in most cases it is necessary to search for lock by sweeping the crystal oscillator frequency[39].

N. Radioactivity

An RFS does not utilize radioactivity, and needs no special precautions for shipping or handling[40, 41, 42].

O. Physics Package Optimization

It is desirable to optimize RFS physics package performance by minimizing the temperature coefficient of its various elements. In the case of an integrated resonance cell, the lamp oven TC can be nulled by adjusting the lamp Rb isotopic ratio [277], and the cell oven TC can be nulled by adjusting the cell buffer gas mixture. In the case of a discrete filter cell that shares an oven with the absorption cell, the lamp oven TC can be nulled with the filter cell length or temperature and the filter/absorption cell TC nulled with the absorption cell buffer gas mixture [287]. If a separate discrete filter cell oven is used, it will necessarily have a fairly large negative TC, but its set point temperature allows nulling of the light shift coefficient [121].

P. RF Synthesis

Nature has not provided us with an atomic resonance at a standard 10 MHz related frequency, but most RFS units need to produce that output[43] and many synthesis schemes have been used for that purpose[44] [5]. The absorption cell buffer gas frequency offset must match the synthesis scheme, and it is desirable that the buffer gas pressure be optimized for a narrow line width, and that it is relatively low to ease its fill tolerance and to reduce barometric sensitivity.

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[35] Bernardo Jaduszliwer developed and verified Python code that implements an updated version of the Kenschaft model in Aerospace Report TOR-2017-02380 of September 2017 (Restricted Distribution).

[36] The discriminator slope is the magnitude of the fundamental signal response per unit of fractional frequency detuning; it is what the physics package "gets paid" to produce, and is optimized as a function of the pumping light intensity, filter and absorption cell (or integrated resonance cell) lengths and temperatures, the RF interrogation power, and the modulation rate and deviation. Excess light and/or RF power broadens the line. Cell temperatures determine the Rb vapor pressure and density. Absorption/resonance cell buffer gas types and partial pressures determine frequency offset. Filter cell length/temperature determines light shift.

[37] Kenschaft's model was implemented mathematically, in block diagram form, and as C language software. Ken Lyon at EG&G devised analog circuit and PC application implementations of it.

[38] Slow FM produces a squarewave recovered signal with transients as the frequency changes, passing through the resonance peak twice per modulation cycle. As the FM rate is increased, this produces a strong 2nd harmonic component with the fundamental component nulled at the center of the resonance line.

[39] Acquisition sweep is quite easy to perform by simply inserting a small offset at the input of the servo integrator. Without a discriminator signal, the control voltage will sweep until it finds the atomic resonance; at that point the signal will overpower the sweep, the system will lock up at a small offset, and the lock detector can then remove the sweep. The acquisition thus happens automatically under control of the lock detector as long as there is adequate recovered signal. During warm-up the acquisition system must sweep up and down until sufficient signal is produced. See Varian U.S. Patent No. 3,364,438 for an early RFS automatic search sweep scheme.

[40] Natural rubidium contains two common isotopes, 72% stable Rb-85 and 28% slightly radioactive Rb-87, a 0.28 MeV beta emitter whose 50 billion year half-life is longer than the age of the universe. A rubidium frequency standard contains under a milligram of Rb-87, and its radioactivity of about 20 pCi is less than that of a banana. Plus, in an RFS, it is surrounded by metallic oven material and magnetic shields.

[41] It can be a hassle to travel by air with an "atomic clock".

[42] Another type of Rb clock is the one used for long-term geological dating by comparing the ratio of Rb-87 to its Sr-87 decay product.

[43] RFS units are sometimes allowed to produce a "natural" frequency output. For example, the EG&G/PerkinElmer/Excelitas GPS satellite Rb clock has a 13.40134393 MHz output, exactly 1/510 of its atomic resonance, which simplifies its RF chain. A VCXO at a direct submultiple of the Rb frequency can also be used with a DDS (e.g., the PerkinElmer LPR10 commercial RFS).

[44] Between 1961 and 1972, atomic clocks were required to make rate (frequency) adjustments so that their time stayed in agreement with the Earth's rotation. This was awkward from both a hardware and an operational standpoint and was abandoned in favor of today's leap second scheme. To comply, some atomic clocks of that era (e.g., the HP 5065A [59]) used synthesizers as so-called "time-scale changers".

One very common RFS synthesis scheme (used by the Efratom RFS units and many others since the 1970's, (see Fig. 14) divides a 10 MHz output crystal oscillator by 2 to 5 MHz and again by 16 (both easy binary factors) to 312.5 kHz, and mixes them additively to 5.3125 MHz. That signal is then subtracted from 6840 MHz from a harmonic and step recovery diode (SRD) multiplier chain to obtain Rb excitation at 6834.6875 MHz, where the SRD also serves as the final mixer. PM is performed near the bottom of the multiplier chain where minimal modulation index is required. A modern version of this scheme substitutes a DDS for the 5.3125 MHz signal, providing tunability and low distortion FM [78], [80].

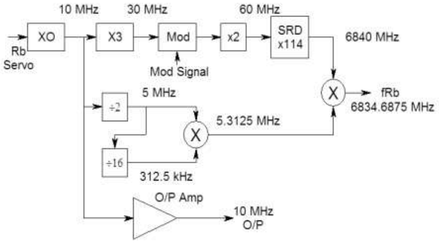

Fig. 14. Popular RFS Synthesizer Block Diagram.

RF chain considerations include buffer gas offset, phase noise, spectral purity, tunability, microwave power stability and modulation distortion.

Q. Servo Modulation

Another distinguishing aspect of an RFS design is the way low frequency FM is applied to its microwave interrogation in order to support synchronous detection in its frequency lock loop. Classically, this was done by applying triangular audio modulation to a varactor diode in an RC network at the lower end of the RF chain to produce squarewave FM. Lower distortion FM can be achieved using an all-pass network [121] since modulation distortion is an important error factor. Nowadays, perfect squarewave FM is applied via a direct digital synthesizer (DDS). Sinusoidal FM has also been, and still is, used [81]. It is usually necessary to avoid modulating the RF output[45].

R. Microwave Cavities

A traditional RFS requires a microwave cavity to produce a longitudinal RF magnetic field to interrogate the Rb atoms at their 6.835 GHz hyperfine frequency. A classic unloaded TE_{011} cavity at that frequency is the size of a coffee mug, which would in turn determine the size of the absorption cell (say 1" diameter and length), the size of the cavity oven, its thermal and magnetic shielding, and the size of the overall unit. Somewhat smaller TE_{111} cavities are widely used, dielectric loading can make the cavity smaller, and other arrangements have been tried, but it is often the case that the design of an RFS starts with the cavity and proceeds outward from there.

It is necessary that the RF H-field be aligned with the DC magnetic bias field, but these do not have to be aligned with the optical axis, as they are in most cylindrical cavities. For example, see the small so-called Jin resonator used in the Symmetricom X-72 [178]. References herein for RFS microwave cavities are [174] through [182].

S. Environmental Sensitivity

AFS environmental sensitivity has been studied quite extensively[46] [82]. The principal RFS environmental sensitivities are:

- Temperature and Temperature Slew
- Thermal and Power Cycling
- Barometric Pressure
- Humidity
- Supply Voltage
- Acceleration, Vibration, G-Sensitivity & Orientation
- Mechanical Shock
- Magnetic Field
- EMI Susceptibility
- Radiation (Total Dose, Transient, SEU)
- Relativity

More details about these sensitivities are given below and herein in references [82] and [83].

T. Baseplate Temperature Control

Active control of external RFS temperature, most often applied via its baseplate in a space application, is an effective way to reduce its overall TC to essentially zero (at the expense of additional power, and some increase in complexity, size and weight). A good example of this is the Excelitas GPS RAFS where an attempt was made by ITT to use software temperature compensation but that was found of limited effectiveness because of the many small internal TC contributors and their differing time constants. Active baseplate temperature control is better. Figure 15 shows the thermal characteristics of a typical baseplate temperature controller (BTC).

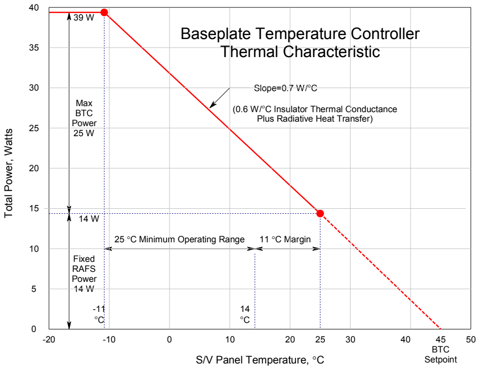

Fig. 15. BTC Thermal Characteristic. In this plot, the warm-up demand power at the left, the set point is at the right, and the operating power range is between the two dots. The slope of the BTC characteristic indicates the thermal conductance of its insulator plus radiative heat transfer.

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[45] Servo modulation on the RF output may be tolerable for an RFS used only as a clock. Another case is when the RFS output is used to drive a DDS, which has the effect of masking the discrete FM sidebands as wideband noise.

[46] Space is a generally benign place for gas cell rubidium frequency standards (e.g., no barometric pressure changes). After launch, except for radiation, these clocks perform well in orbit, and radiation exposure can be managed by proper component selection, screening and shielding. The Rb physics package itself is not particularly sensitive, and zero-g operation is not a problem. Tin whisker growth is a concern for all space electronics. Magnetic torquer interference is another concern for an Rb clock onboard a spacecraft.

U. Vibration Sensitivity

In general, an RFS is less sensitive to mechanical vibration than a quartz crystal oscillator. Nevertheless, vibration can affect the stability of an RFS, and this can be an important consideration in tactical environments. That sensitivity is mainly associated with two mechanisms: (a) disturbance of the physics package light beam when the vibration frequency is at or near that of the servo modulation, and (b) disturbance of the quartz crystal oscillator when the vibration is at or near twice that of the servo modulation[47]. The former is reduced by a rigid physics package construction, while the latter may require a crystal resonator with low acceleration sensitivity or active compensation. Both can be reduced by vibration isolation, although that is awkward at low vibration frequencies. References herein for RFS acceleration, vibration and g sensitivity are [186] and [187].

V. Fast Warm-Up

Fast warm-up can be a requirement for some RFS applications. That process involves lamp starting, oven warm-up, frequency servo lockup and physics package thermal stabilization. Lamp starting can be immediate, particularly if aided by boosted RF power, a HV electrode or even photoionization. Fast oven warm-up involves not only excess demand power but, more importantly, applying it directly to the internal physics package elements. Servo lock acquisition can be speeded up by special circuitry such as fast sweep and a fundamental signal detector. An EG&G fast warm-up missile borne RFS design was able to achieve lockup in only 7 seconds from +5°C [155].

W. Radiation Hardening

Some applications require that an RFS be hardened again nuclear radiation, for example when the unit is intended for a space or military environment. This may have design impact on both the physics package and the supporting electronics. It was a significant consideration for tactical RFS units in the 1980's at the end of the cold war, and still is for GPS satellite clocks[48, 49, 50]. References herein for RFS radiation hardening are [206] through [209].

X. Transient Radiation

Few RFS units have to contend with transient radiation, but those that do require special design considerations because their large area photodetectors are excellent radiation sensors whose response can upset the frequency control servo. One effective means of hardening disables the servo until the unit can recover[51, 52].

Y. High Temperature Operation

High temperature RFS operation requires that their oven set points be raised sufficiently to maintain temperature control. That can reduce the Rb discriminator signal and compromise performance. A small (thin) absorption cell is advantageous. Raoult's law can be utilized to depress the Rb vapor pressure by using a mixture of another alkali element such as potassium. The Rb vapor pressure characteristic is fundamental to RFS physics package design [234].

Z. Power Cycling Endurance

Power cycling endurance is a critical aspect for RFS units that must operate intermittently, especially if fast warm-up is also required. Careful physics package thermal design is needed to assure that fatigue stress is minimized. Design verification and/or ESS testing is necessary to assure acceptable warm-up endurance, which applies especially to an RbXO (See: EG&G RbXO and [156] through [159]).

AA. RFS Testing

RFS testing has also been studied quite extensively and is described in Reference [84]. In general, the electrical and mechanical aspects are much the same as any electronic instrument, but RFS testing requires high resolution frequency measuring equipment and attention to its specific environmental sensitivities. References herein for RFS testing are [84] through [110].

BB. Rubidium Masers

Active rubidium masers were investigated in the early days of Rb atomic clock research, notably by Jacques Vanier and his group at Laval University, and by W. Stern, P. Davidovits and R. Novick. While excellent short-term stability was obtained, these devices had all of the disadvantages of the H-maser (size, complexity) without any real advantages, and work on them ended without any commercial units ever being made[53] [217].

CC. RFS Evolution

The general evolution of rubidium frequency standards can

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[47] The effect of phase noise on the microwave interrogation signal at twice the servo modulation rate (and the related $2f_{mod}$ EMI or vibrational modulation effect) was elucidated by R. P. Kenschaft in a 1969 appendix to a General Radio unpublished design report [135] but was not widely appreciated until a 1991 IEEE I&M paper by C. Audoin, et al. [160].

[48] RFS radiation hardening generally involves total gamma dose, neutron/proton fluence, transient radiation and single event upset considerations. Their physics packages are quite immune except for the photodetector. Their electronic hardening is similar to most such circuitry, and centers on the analog circuitry.

[49] An RFS radiation hardening analysis has the very desirable side effect of also performing a detailed worst case circuit analysis by a highly-skilled analyst (e.g., Terry Flanagan/IRT, Dave Swant/GE for GPS clocks). Modern circuit analysis tools are remarkably effective. That modeling relates closely to initial and end of life (EOL) performance margins. Furthermore, this information is important for verifying component stress levels and making reliability predictions.

[50] Ken Lyon/EG&G is an amateur entomologist. During total gamma dose RFS tests, he would place a bug in a matchbox near the unit under test. After one test at U. Mass. Lowell, the poor thing turned a sickly grey (at about a human fatal 10k rads). But amazingly it recovered to apparent full health after a few days.

[51] The effect on clock time error is probabilistic, depending on when during the servo modulation cycle the event occurs. Thus it is necessary to perform many FXR shots to determine a worse case. Ken Lyon and I held the record for the most shots in a day at the GE Valley Forge facility.

[52] An FXR machine is an impressive device. Its thick Ta target is deformed by the energy delivered to it by the electron beam. The TRW machine we used in El Segundo had (for a few nanoseconds) more power than all of LA.

[53] Active Rb masers were made using both buffer gasses and wall coatings (e.g., paraflint wax). They require large high-Q cavities to self-oscillate (a passive RFS operates at only about 1% of the oscillation threshold). Jacques Vanier worked on an Rb CPT maser at Kernco.

be roughly summarized in a timeline as follows:

- Scientific Research (1950’s)
- Commercialization (1960’s)
- Miniaturization (1970’s)
- Tactical Military (Final Cold War Era 1980’s)
- Telecom (2000’s to Present)

This timeline is, of course, only approximate. The early period of scientific research first spans investigations into atomic structure and then ways to utilize that structure in atomic clocks. That research underwent commercialization as laboratory apparatus evolved into products. Miniaturization, simplification and cost reduction followed, which greatly expanded atomic clock applications. Meanwhile, a period of military buildup resulted in a demand for environmentally-hardened RFS units. Today, while laboratory and military applications still exist, the vast majority of Rb clocks are used for telecom timing.

DD. RFS Technological Lines of Heritage

Before beginning a detailed look at some of the organizations involved with RFS technology, it seems wise to present an overview of the leading current participants and their historical heritage. The following list shows the technology originators and their successor organizations and names:

- Varian, General Radio, GenRad, EG&G, PerkinElmer, Excelitas
- R&S, Efratom, Ball, Datum, Symmetricom, Microsemi. Microchip
- Litton, Frequency Electronics
- Stanford Research
- Neuchatel Observatory, Temex, Spectratime, Orolia
- Tadiran, Time & Frequency Ltd., Accubeat

A timeline of some of these RFS organizations is shown in Fig. 16, and references herein for RFS products from some from these organizations are [59] through [81].

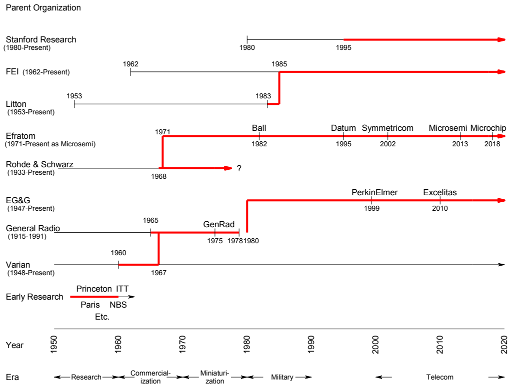


Fig. 16. RFS Organizational Timeline. For GPS rubidium clocks, there are two timelines: Blocks I, II, IIA: Rohde & Schwartz, Efratom, FTS/NRL/NTS-1, Efratom/Rockwell/Autonetics and Blocks IIR, IIR-M, IIF, III: Varian/General Radio/GenRad, EG&G/PerkinElmer/Excelitas.

IV. ORGANIZATIONS AND PEOPLE

The history of rubidium frequency standard products can best be traced through the organizations and people that worked on them.

It is interesting that the emphasis of the early RFS manufacturers was on performance, which in many respects exceeded that specified for many of today’s commercial units. That is due primarily to the relatively large size of the early physics packages which used large TE_{011} cavities, large and cool absorption cells and discrete filter cells, along with high performance ovenized crystal oscillators. This was before the emphasis shifted to small size and low cost. The early RFS units were used as local frequency standards, where high stability and low aging were paramount. Today most RFS are used as holdover devices in timing applications where they are locked to a GPS reference most of the time and simply need to maintain microsecond timing for a few days until the GPS reference is restored. The modest-performance RFS is simply a more economical way to accomplish that than a very high performance ovenized crystal oscillator.

A. Early RFS Manufacturers

Several (mainly aerospace) companies were the first to offer commercial RFS units, as listed below. Besides their use as laboratory frequency references, RFS were used in the late 1960’s by TV networks to synchronize color broadcasts.

1) General Technology

General Technology of Los Angeles, CA developed one of the first commercial rubidium frequency standards, the Model 304 (see Fig. 17).

Fig. 17. General Technology 304-B RFS. Photo Credit: Univ. of Queensland, Australia.

2) Tracor

Tracor acquired General Technology in 1962 and continued to make the Model 304 RFS and other T&F products (e.g., the Model 527E frequency difference meter). There was also a Tracor Model 308 RFS (see Fig. 18).

Fig. 18. Tracor Model 308A RFS. Photo Credit: eBay.

3) Space Technology Laboratories

Space Technology Laboratories (STL) in Redondo Beach, CA, a subsidiary of Thompson Ramo Wooldridge (TRW), now Northrop, and a predecessor to the Aerospace Corporation, made some of the first commercial RFS in the early 1960's. Especially noteworthy was their 1961 launch on Atlas rockets as a test for missile guidance. The principal RFS technologists at STL were J. M. Andres, D. J. Farmer, and G. T. Inouye [51].

4) *Clauser Technology*

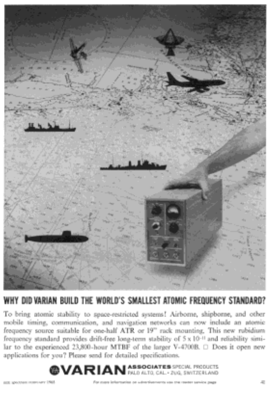
Little information is available about Clauser Technology Corporation of Torrance, CA which was founded by Milton U. Clauser (1913-1980) who was previously a VP at STL. The company operated briefly between 1960 and 1962, and had some RFS-related activity.

5) *Varian*

Varian Associates were a major contributor to early RFS technology. The Model V-4700A Rubidium Vapor Frequency Standard was introduced in early 1962 by the Instrument Division of Varian Associates of Palo Alto, CA (see Fig. 19). It is believed to be the first commercially available RFS on the market. The Packard and Swartz December 1962 *IRE Transactions on Instrumentation* paper about it had stability data taken in October 1961 [34]. The design was remarkably similar to today's high-performance (analog) units. It was all solid-state except for the ≈ 100 MHz lamp exciter, which used a pair of triodes in a push-pull oscillator configuration. The optical package had an Rb-87 lamp, a discrete Rb-85 filter cell, and an Rb-87 absorption cell with an N_2-Ar buffer gas mixture. The unit had 5 MHz, 1 MHz, and 100 kHz outputs, the latter two obtained via regenerative dividers. The synthesizer drove a varactor diode multiplier with signals at 120 MHz and 5 6/19 MHz, the latter produced by a divide-by-19 regenerative divider and a balanced modulator. The ≈ 5.3158 MHz synthesizer output was subtracted from the 57th harmonic of 120 MHz at 6840 MHz in the multiplier to produce an interrogation signal at the ≈ 6834.6842 Rb resonance, corresponding to a relatively small buffer gas offset of about 1.6 kHz. The interrogation signal was modulated at 107 Hz by a phase modulator at the bottom of the RF multiplier chain, which had many tuned circuits. The discriminator signal from the optical package was amplified, filtered, synchronously demodulated with fundamental and 2nd harmonic detectors, and integrated to produce a control voltage for the 5 MHz crystal oscillator. All of this circuitry is familiar today, although the modular chopper-stabilized operational amplifiers are a far cry from today's IC op amps. All-in-all, it appears to be a very workmanlike design, and at least one unit may still be in use today [58].

Fig. 19. Varian V-4700A. The 1st commercial rubidium frequency standard. Photo Credit: Varian Associates

The Varian R20 rubidium frequency standard was the successor to the V-4700A circa 1965 (see Fig. 20).

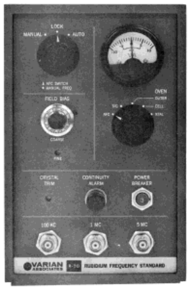


WHY DID VARIAN BUILD THE WORLD'S SMALLEST ATOMIC FREQUENCY STANDARD?

To bring atomic stability to space-restricted systems! Airborne, shipborne, and other mobile timing, communication, and navigation networks can now include an atomic frequency source suitable for one-half ATR or 19" rack mounting. This new rubidium frequency standard provides drift-free long-term stability of 5×10^{-11} and reliability similar to the experienced 23,800-hour MTBF of the larger V-4700B. ☐ Does it open new applications for you? Please send for detailed specifications.

VARIAN ASSOCIATES SPECIAL PRODUCTS
PALO ALTO, CAL. • ZUG, SWITZERLAND

(Left) February 1965 Varian Ad in *IEEE Spectrum* for "World's Smallest Atomic Frequency Standard".



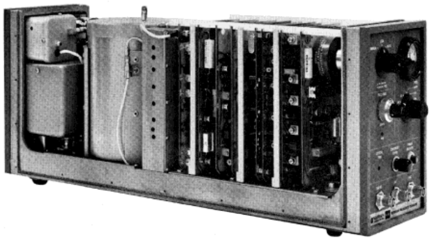


Fig. 20. Varian R-10 Rb Frequency Standard. Credit: Varian Associates.

The Varian Quantum Electronics Division had operations in Palo Alto, CA and at Bomac in Beverly. MA. Most of the Rb gas cell activity was in Palo Alto, with Cs beam tube and active H maser work in Beverly (next to where FTS/Datum/Symmetricom/Microsemi is still located[54]). When those activities ceased in 1967, Varian retained their Rb magnetometer product line and General Radio continued their Apollo era contract work on an Rb space clock for NASA.

The principal RFS investigators at Varian were W. Earl Bell, Arnold L. Bloom, Martin Packard, B.E. Swartz, Art McCoubrey and Al Helgesson (see Fig. 21)[55, 56] [34].

W.E. Bell
(1921-1991)
Photo Credit: Spectra Physics.

No
Photo
Available

A.L. Bloom
(1923-2018)

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[54] Microchip Technology acquired Microsemi in 2018.

[55] Art McCoubrey later was associated with (a "co-founder" along with Bob Kern in 1971) Frequency and Time Systems in Danvers and then Beverly. MA. They did not pursue RFS technology until much later as Datum, but did help to introduce the Efratom unit in the U.S. We at General Radio explored an integrated cell Rb physics package for him shortly after that.

[56] Al Helgesson was instrumental in the Rb technology transfer from Varian to General Radio in 1967.

Martin Packard
(1921-)
Photo Credit: Stanford Univ.

Byron E. Swartz
(1931-)
Photo Credit: IRE

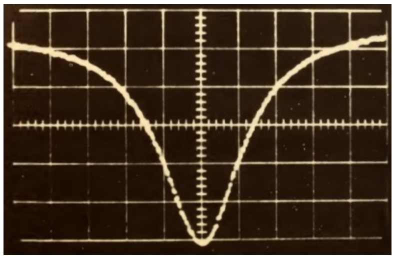
Art McCoubrey
(1920-2019)
Photo Credit: Legacy.com.

Al Helgesson
(1933-)
Photo Credit: IEEE.

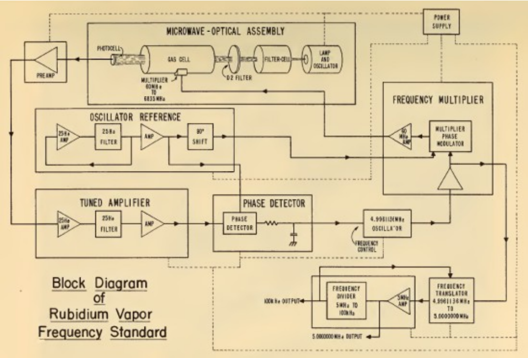
Fig. 21. Key RFS Investigators at Varian.

6) *NBS/Varian*

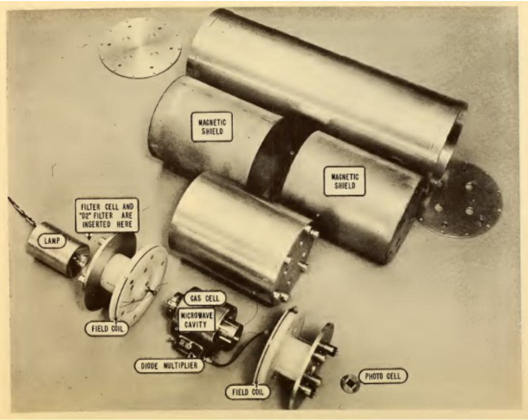
NBS started work in 1959 on a portable RFS for a satellite gravitational redshift experiment (see Fig. 22) [51]. The experiment was "deferred", but three units were built using a Varian physics package and a "natural frequency" 4.9961136 MHz crystal oscillator (multiplied by 3·2·2·114 to the Rb hyperfine frequency, with a separate "translator" to 5 MHz). This unit illustrates how advanced this technology was at that early date.



Rb Resonance Line



Block Diagram



Photograph of Physics Package

This physics package, with its TE_{011} cavity, resembles the first General Radio designs.

Fig. 22. NBS Portable RFS [51]. Photo Credit: NBS.

B. *Major RFS Instrument Manufacturers*

Quartz crystal oscillator laboratory frequency standards were a part of the standard product line for electronic instrument manufacturers such as Hewlett-Packard, General Radio and Rohde & Schwarz, so it was natural for them to enter the field of atomic frequency standards in the early 1960's when those instruments started to become feasible. This traditional market was quite limited, and was, to some degree, based on the need to offer a complete product line.

1) *Hewlett-Packard*

Hewlett-Packard, while emphasizing cesium beam tube atomic frequency standards, also developed and manufactured a high-performance laboratory RFS, the 5065A (see Fig. 23)[57], The HP Rb technology was independently developed with some heritage from Varian. The principal contributors were Darwin Throne (project leader), B. E. Swartz (electronics, from Varian) and R. A. Baugh (optical package).

Fig. 23. HP 5065A Rubidium Frequency Standard. Photo Credit: Hewlett Packard [62].

The HP 5065A had (and a few units still operating have) excellent performance and it is probably the best laboratory RFS ever made. HP also developed a miniature HP 10816 RFS in the late 1970's that was never produced[58].

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[57] The Varian Cs technology (e.g., Len Cutler) was transferred to HP in Beverly, MA (and later Santa Clara, CA) and the H-maser technology (e.g., Bob Vessot) was transferred to the SAO in Cambridge, MA.

[58] Information about the HP mini RFS was kindly provided to me by R. K. "Rick" Karlquist. He was the RF engineer on the project.

2) General Radio/GenRad

General Radio (later GenRad, abbreviated GR) was, between 1915-1991, a leading manufacturer of electronic instruments, including a complete line of time and frequency products. After many years of making quartz crystal frequency standards, it established its own rubidium gas cell technology circa 1965, later augmented by similar Varian technology.

Fig. 24. General Radio Concord MA Plant Circa 1965.

The GR RFS activities emphasized military and aerospace designs rather than the company's traditional commercial products. Photographs of two of those RFS units are shown in Figs. 25 and 29, and details of the SATS physics package are shown in Figs. 26-28. It used a combination of General Radio and Varian technology[59].

The Collins physics package was similar to that used in the SATS but included a thermoelectrically cooled sealed outer oven [145].

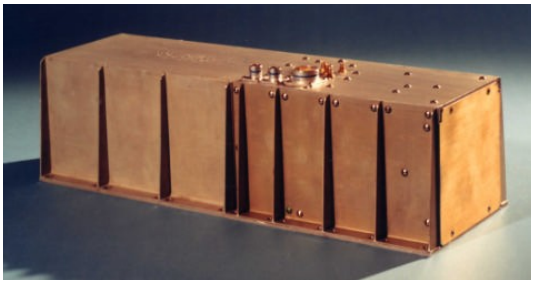

Fig. 25. Spacecraft Atomic Timing System (SATS). The SATS unit comprised both a rubidium frequency standard and a digital clock and time code generator. Photo Credit: General Radio.

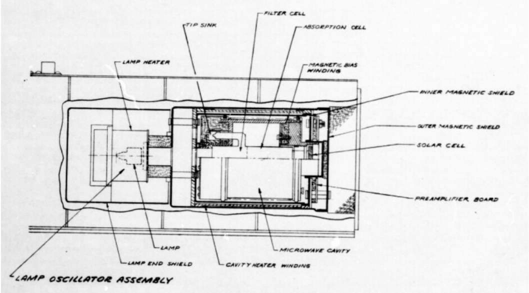

Fig. 26. SATS Physics Package Cross Section. Photo Credit: General Radio.

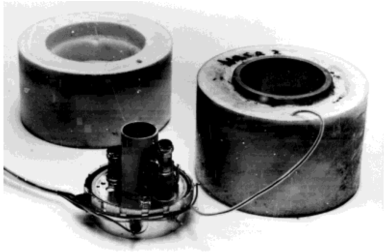

Fig. 27. SATS Physics Package Lamp Assembly. Photo Credit: General Radio.

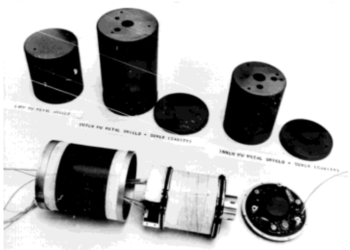

Fig. 28. SATS Physics Package Cavity Assembly. Photo Credit: General Radio.

Fig. 29. Collins Radio AFS-81 Military RFS..The AFS-81 contained an Rb physics package made by General Radio. Photo Credit: Collins Radio.

The work on rubidium frequency standards began at the General Radio Company in about 1965 as a logical successor to its traditional quartz frequency standard product line when it became clear that the last such quartz crystal oscillator, the GR Model 1115, would be supplanted by the rapidly-emerging atomic clocks. This work started at the Concord. MA headquarters and was subsequently moved to the new Bolton, MA facility. The principal contributors toward rubidium frequency standard technology at General Radio were as follows (see Fig. 30):

- Richard W. Frank Engineering Group Leader
- Herbert P. Stratemeyer Engineering Project Manager
- William J. Riley, Jr. Electronic Engineer
- Roland P. Kenschaft Physicist
- John E. Wilhelm Electronic Engineer
- Richard A. Mortenson Mechanical Engineer
- William J. DeFlorio Glassblower

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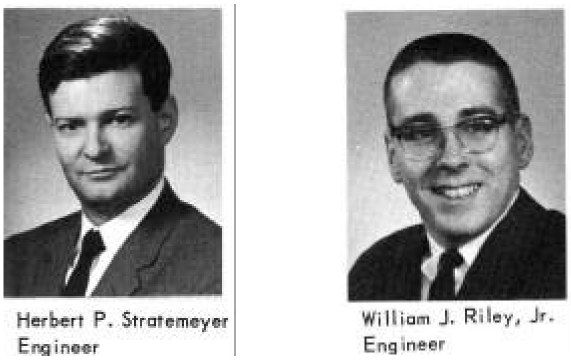
[59] Although the SATS lamp and cavity assemblies are basically the same as a modern RFS unit, it interesting to note some of the differences between it and the GPS RAFS that followed. The SATS filter and absorption cells shared the same oven and had long tubulations. The SATS ovens used urethane foam rather than vacuum insulation and used bifilar heater windings rather than double layer foil heaters. The SATS lamp exciter circuit was inside the lamp oven and used somewhat unreliable piston trimmers rather than ceramic chip capacitors. The SATS cavity mode was TE$_{011}$ rather than a smaller TE$_{111}$ and it had an unnecessary waveguide below cutoff at its photodetector.



Herbert P. Stratemeyer
Engineer

William J. Riley, Jr.
Engineer

Fig. 30. RFS Developers at General Radio. Photo Credit: 1969 GR Personnel Book.

The major rubidium frequency standard projects and products developed and produced at General Radio were as follows:

- Model 1118 Commercial Rubidium Frequency Standard (never produced)
- Spacecraft Atomic Timing System (SATS) for NASA (developed and qualified)
- Model 1122 Military Rubidium Physics Package for Collins Radio (about 300 produced)
- Missileborne RFS for General Electric (design study)
- Airborne RFS for Magnavox (design study)
- Model 1126 Space Rb Clock for Rockwell Global Positioning System (GPS) (brassboard unit)

The initial investigations of rubidium frequency standard technology were conducted with company R&D funding. Earlier work by Maurice Arditi at ITT and others had established the viability of this technology. The work proceeded quite independently of outside help or support, except for some initial consultation by Peter Bender of NBS on Rb cell/buffer gas technology. General Radio had expertise in frequency control, quartz crystals, flash lamps, high vacuum processing and RF/microwave electronics. The first cells were made at the EG&G Bedford laboratory before suitable glassworking and cell processing facilities were established at GR. The core GR rubidium frequency standard technology used a pure Rb-87 lamp, a discrete Rb-85 isotopic filter cell, and an Rb-87 absorption cell. Reasonably good lamp life was obtained by the use of alkali-resistant glass and burn-in (calorimetric process control did not exist). The lamps were generally operated in the intense, high-temperature red mode. Light shift was nulled by varying the length (or later) temperature of the filter cell. Excellent aging was obtained by ultra-high (ion pump) absorption cell processing. All designs until the final GPS one used a full-size TE_{011} microwave cavity that held both the filter and absorption cells at the same operating temperature. The GPS unit used a smaller TE_{111} cavity and a separate filter cell oven.

An important early milestone was the closing of the Varian Quantum Electronics Division in Beverly, MA and the assumption by General Radio of their NASA contract to develop a Spacecraft Atomic Timing System for the Apollo program. It was a combination of a rubidium frequency standard, digital clock and time-code generator. That unit, completely redesigned at GR, was qualified but never produced or flown.

Overall, the most significant production activity was the Model 1122 Rb physics package, developed in collaboration with Marv Frerking and Don Johnson of the Collins Radio Company. Initially intended for an airborne collision avoidance system (CAS)[60], it ended up being used in the U.S. Navy Verdin "doomsday" VLF communication system. Collins (later Rockwell) built the complete AFS-81 militarized rack-mounted rubidium frequency standard while GR made the physics package (which included its power supply, oven controller, RF multiplier and preamplifier supporting circuits). This unit was extremely rugged, operated under harsh environmental conditions (including thermoelectric cooling for high temperatures and a sealed physics package to avoid barometric sensitivity in airborne use), and provided high performance (even by today's standards).

This work was carried out by an informal "aerospace" group that operated somewhat independently from the commercial products because of its contract work and the need for military parts, quality systems and testing. Those activities were supplemented by other contract work such as quartz crystal measuring equipment (Microelectronic Bridge and Tracking Servobridge Detector) for the U.S. Army. It is interesting that these early RFS products had relatively high performance compared with today's miniature units. They were, however, much more complex and expensive. Even commercial units were the price of a car, while the ones now used in large quantities for commercial telecom applications are only about 5% of that relative cost.

The missileborne and airborne RFS design studies emphasized performance under vibration, and it was recognized that vibrational modulation of the crystal oscillator that produced the interrogation signal was critical at frequencies related to the servo modulation. R. P. Kenschaft contributed important theoretical insight into the Rb recovered signal and its processing.

The final major project was the development of a high-performance rubidium clock for the Rockwell Global Positioning System (GPS). That effort resulted in a smaller physics package and a new electronic design intended for space. In the meanwhile, Rockwell's own Autonetics division was adapting an Efratom physics package for the same application. The GR GPS design was not pursued until several years later at EG&G.

The RFS work at GR wound down in around 1978 with the retirement of Dick Frank and Herb Stratemeyer and the departure of Bill Riley. John Wilhelm continued to support the Rockwell physics packages for a while, but no new projects were undertaken. The company was in the process of transitioning from electronic instruments to automated test equipment, and never regained its former leadership position. The main legacy of the General Radio rubidium frequency standard technology is the GPS RAFS units built by EG&G (later PerkinElmer, now Excelitas). Those are a direct descendant of the GR Rockwell GPS RFS design, and were refined into the

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[60] The 1970's aircraft Collision Avoidance System (CAS) would have worked somewhat like GPS with precisely synchronized clocks and pulses whose time of arrival indicates proximity.

highest performance such units ever made. That work was carried on at EG&G by W. J. Riley, with initial consultation by H. P. Stratemeyer.

3) Rohde and Schwarz

Rohde and Schwarz was, as still is, a major electronic instrument manufacturer, and, much like General Radio and Hewlett-Packard, had a line of time and frequency products, including laboratory rubidium frequency standards.

Their first rubidium frequency standard (I believe) was the XSR laboratory RFS developed in 1968 and shown in Fig. 31[61]. The XSRM shown in Fig. 32 was a later R&S RFS.

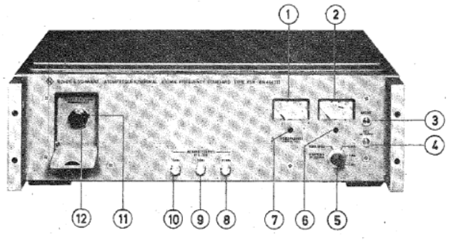

Fig. 31. R&S XSR Rubidium Frequency Standard. Photo Credit: R&S.

Fig. 32. Rohde & Schwarz XSRM RFS. Photo Credit: Rohde & Schwarz.

C. Aerospace/Electronics RFS Contractors

Several major aerospace/defense contractors became involved with rubidium frequency standard technology, mainly because of their own requirements or those of their Government customers.

1) Rockwell International

Rockwell (in Seal Beach, CA, now Boeing) was the first contractor for GPS satellites (1st contract awarded June 1974). They, along with their Autonetics division (in Anaheim, CA) needed Rb clocks for this program, and opted to design an RFS based on an Rb physics package from Efratom in Munich, Germany, which set up operations in Irvine for that purpose (see Fig. 33)[62]. The effort was quite successful (although there were some early in-orbit failures), The principal engineers involved were Hugo Fruehauf and Dale Ringer at Rockwell, Chuck Wheatley and Frank Kopek at Autonetics, and Werner Weidemann at Efratom.

Fig. 33. Rockwell GPS RFS. This atomic clock was built for the first GPS satellites in the late 1970s [119]. Photo Credit: Smithsonian Museum.

D. EG&G/PerkinElmer/Excelitas Technologies

EG&G entered the rubidium frequency standard business in 1980 at the request of the U.S. Air Force and Rockwell International. The EG&G facility in Salem, MA was a logical place to pursue this work because of their expertise in glassworking and high vacuum technology, and their familiarity with high reliability critical defense programs (see Fig. 34)[63, 64, 65].

Fig. 34. Excelitas (right building) in Salem, MA. EG&G opened its Salem, MA plant at 35 Congress Street in the Shetland industrial park, the old Naumkeag Steam Cotton works on the Salem waterfront, in 1961. The Rb department began activities in 1980 on the development of a GPS clock. That work continued as PerkinElmer (1999) and now Excelitas today. Photo Credit: Shetland Properties.

The major contributors to the RFS work at EG&G are shown in Fig. 35.

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[61] The Rohde & Schwartz XSR RFS was developed in 1968 per a May 2007 e-mail from Hans H. Jucker of R&S who kindly sent me a data sheet for it.

[62] Excerpt from The Origins of GPS: "On realizing that the small Efratom company would be incapable of producing a radiation-hardened, space-qualified rubidium oscillator, RI's GPS satellite program manager Richard Schwartz created a teaming relationship with them, which included his chief engineer, Hugo Fruehauf, plus Dale Ringer, Dr. Chuck Wheatley of Rockwell's Autonetics Division, and Efratom's Werner Weidemann. With heroic efforts, this team built a space-qualified clock in time for the first GPS launch in February 1978."

[63] The author worked on RFS technology at EG&G and consulted for them after they become PerkinElmer and then Excelitas. I am therefore able to describe some of those activities in greater detail. I would welcome similar detail by people associated with the work done at other organizations.

[64] The U.S. atomic clock business has traditionally been centered in the Boston area and Southern California.

[65] Why were and are so many of the atomic clock companies in the Boston area? Well I suppose it just started there (and Palo Alto) and has just kept going. Bomac/Varian/FTS/Datum/ Symmetricom/Microsemi all in nearly the same place with spinoffs to General Radio/GenRad/EG&G/Perkin Elmer/Excelitas, as well as Kernco, National (Atomichron), Pickard & Burns, and the SAO. There would sometimes be so many of us on the way to the FCS or PTTI that we could have presented papers on the plane.

EG&G Group Scientist Sy Goldberg (1927-2014, at left) with EG&G co- founder Harold "Doc" Edgerton examining an RFS-10 rubidium frequency standard in 1983. Photo Credit: EG&G.

Sy Goldberg

Bill Riley

Tom Lynch

Ken Lyon

John Vaccaro

Doug Lowrie

The EG&G Salem general managers included Walter Saldarini, Len Colasanti, Paul Beech and Arnie Shuman. The Rubidium department managers included Bob Stitt, Ralph Carpenter, Ed Bryant, Mal Schwalje, Walt Zarris and Murray Tysinger[66].

Fig. 35. Major RFS Contributors at EG&G.

The EG&G Electronics Components Division and Frequency Products Division in Salem, MA (as it was called during the 1990's) was managed by a variety of persons under several structures, while the technical staff remained largely stable and self-sufficient.

1) EG&G GPS RAFS

The history of the exceptionally high performance EG&G (later PerkinElmer and Excelitas) GPS Rubidium Atomic Frequency Standard (RAFS) is a prominent part of this history paper[67, 68, 69, 70]. These clocks (see Fig. 36) have significantly higher performance than their smaller commercial counterparts, e.g., a short-term stability better than $1x10^{-12}\tau^{-1/2}$, a flicker floor below $1x10^{-15}$, a temperature coefficient on the order of $1x10^{-14}/^{o}C$, and aging under $1x10^{-12}$/month. They easily maintain time to better than 1 nanosecond over a day onboard a GPS satellite, which corresponds to a range error of 1 foot[71]. About 100 of these Rb clocks are currently in-orbit.[72]

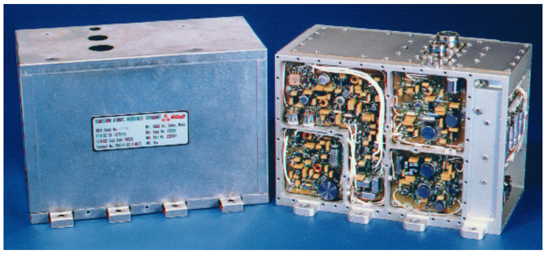

Fig. 36. EG&G GPS Block IIR RAFS. Photo Credit: EG&G

The story begins at General Radio in the mid-1970's with the adaptation of an Rb physics package built for Collins Radio (later Rockwell) as part of the U.S Navy VERDUN VLF communication system [145]. That design used a full-sized TE$_{011}$ microwave cavity and had separate lamp and cell (cavity) foamed-in-place ovens inside a sealed main oven which desensitized it from pressure changes in aircraft use. The initial GPS design, performed for Rockwell as part of their first GPS satellite program, eliminated the outer oven and substituted a smaller TE$_{111}$ cavity, and a separate filter cell oven, and was successfully completed through a brassboard phase [120]. The principle contributors to that design at GR were Herb Stratemeyer, Dick Frank and this author.

Later, in 1980, when Rockwell was experiencing Rb lamp reliability problems with their own GPS clock that used an adapted Efratom physics package [119], work on the GR-based RAFS was continued at EG&G under the leadership of this author with major contributions from Sy Goldberg and Tom Lynch, and early consultation by Herb Stratemeyer and

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[66] The first manager of the EG&G Rb department was Bob Stitt. Murray "Butch" Tysinger was the manager of EG&G Frequency Products when, at its largest, it included a crystal company called CINOX. Len Colasanti was the EG&G Salem division manger during the critical years when the GPS RAFS entered production.

[67] Major contributors to the EG&G GPS RAFS design: At EG&G: Herb Stratemeyer, Bill Riley, Sy Goldberg, Tom Lynch, Ken Lyon, John Vaccaro. At ITT: Tony Baker, Gerry Freed, Marv Epstein, Jay Phelan. At Aerospace: Phil Talley, Charlie Volk, Jim Camparo.

[68] A significant amount of credit for the success of the EG&G GPS RAFS can be attributed to its long gestation period, and to the cordial relationship that developed between the technical staffs at EG&G, ITT and Aerospace Corporation. There was a strong belief in its worth, and a genuine team effort to make it the best it could be.

[69] The contract with ITT for the GPS Block IIR Rb clocks was extremely important to the EG&G Rb department. It led to a very mutually beneficial relationship that still continues today. The RAFS has proven to be an excellent clock, and close personal ties have developed between the technologists in both organizations.

[70] It's impossible to overstate the importance of GPS to the RFS business. Besides the satellite clocks themselves, it spawned a huge market for commercial RFS units in telecom cell sites. Of course, the opposite is also true: Rb clocks have been the most critical devices onboard the GPS satellites.

[71] It was originally planned to deploy a mix of two rubidium and one cesium clock on the Block IIR GPS satellites. When the Kernco/SCI Cs team foundered, the decision was made to go with three EG&G RAFS. This, of course, increased the pressure on us to achieve the performance and reliability goals. For added assurance, two units were placed on life test at NRL [168]. Fortunately, those RAFS met and exceeded all requirements.

[72] 60 GPS IIR, 24 GPS IIF, 3 GPS III, 11 QZSS as of June 2019. Many have operated for 10-15 years, one for 20+ years.

Jacques Vanier[73, 74], along with close cooperation with the Aerospace Corporation.

To the credit of Rockwell and their U.S. Air Force sponsors, the program was set up with sufficient time and resources to do a careful bottoms-up design of a GPS-specific advanced Rb clock. A principal immediate goal was to solve the lamp reliability problem. The physics package was tailored for high-performance space operation (e.g., the ovens used vacuum insulation, had low radiative thermal loss, and high reliability low residual magnetic field 2-layer foil heaters with high gain temperature controllers). The EG&G RAFS design retained the performance advantages of a discrete filter cell (e.g., high S/N, absorption cell homogeneity, low RF sensitivity, ease of light shift nulling) while overcoming its main disadvantage (large negative filter cell TC) by tight oven temperature control.

The lamp Rb depletion problem on the Rockwell/Efratom GPS clocks was aggregated by using low Rb fill to reduce noise, but this was hard to control "by eye" and it resulted in short (e.g., 1 year) lifetime. Aerospace scientists Jim Camparo and Charlie Volk established that the likely depletion mechanism was diffusion of Rb into the glass lamp envelope. Tom Lynch at EG&G invented a non-destructive way to measure lamp Rb fill by measuring the energy required to melt it using a differential scanning calorimeter (DSC). Employing that for initial process control and subsequent lamp screening, the Rb fill and diffusion rate were quantified, and fill tolerances established to assure both low noise and long life[75]. That methodology is now in widespread use throughout the RFS industry.

In summary, Rockwell opted to continue using its own in-house (Autonetics in Irvine) GPS RFS design using the Efratom physics packages rather than further develop a 2nd source at GR. The EG&G GPS RFS concept lay dormant until the Lockheed Martin/ITT GPS Block IIR program. Design work at EG&G began in 1990, a production contract was awarded in 1992, and clock deliveries (60 clocks, 3 per satellite) occurred between 1994 through 1997. GPS Rb clock references herein are [119] through [132][76].

2) First GPS IIR Launch

The first GPS IIR satellite launch in January 1997 failed shortly after liftoff when a damaged Delta solid rocket booster exploded. The three on-board RAFS were recovered largely intact but in non-operable condition as shown in Fig. 37.

Fig. 37. GPS Block IIR RAFS S/N 004. Photo Credit: USAF.

3) Later GPS RAFS Units

Improvements were made in the GPS Block IIF RAFS, including Xe lamp buffer gas, optical filtration and tighter BTC thermal control, which enhanced its stability[77, 78, 79]. Figure 38 shows a cross sectional diagram of the PerkinElmer GPS Block IIF RAFS physics package. That clock included a secondary loop that produced a 10.23 MHz output.

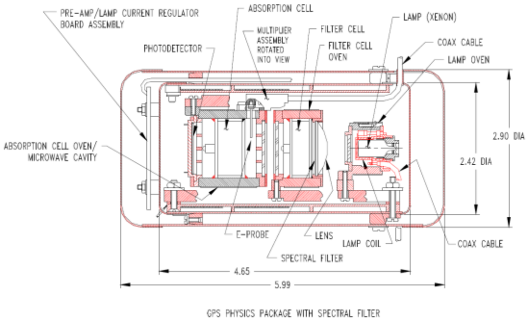

Fig. 38. PerkinElmer GPS Block IIF Physics Package Cross Section. Credit: PerkinElmer.

The Rockwell Block IIF GPS satellites contain both Rb and Cs clocks, allowing their performance to be compared, as shown in Fig. 39. While both types of clock easily meet the IIF specifications, the EG&G RAFS contribute significantly lower range error.

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[73] Jacques Vanier and his atomic clock group at Laval University researched absorption cell buffer gasses and other aspects of the initial EG&G GPS RAFS design.

[74] Jacques is one of the giants of this field. He (along with Claude Audoin) literally "wrote the book" about atomic clocks [3]. He was one of the principals at the Varian Quantum Electronics Division in Beverly, MA. He established a quantum electronics laboratory at Laval University, pioneered active and passive Rb frequency standards, researched wall coatings and buffer gases, analyzed RFS electronics, modeled the Rb signal, and then later largely invented the CPT interrogation technique, implementing it in ordinary and "maser' form at Kernco.

[75] Zero in-orbit GPS RAFS Rb lamp failures have occurred since adopting DSC lamp screening. A somewhat similar but less severe issue regarding lamp Xe buffer gas fill was resolved more recently by non-destructively measuring the Xe buffer gas pressure by operating the lamp as an absorption cell and measuring its frequency offset.

[76] EG&G in Salem also made Rb magnetometer lamps, cells, lamp exciters and physics packages for a sister division, Geometrics.

[77] An RFS radiation hardening analysis has the very desirable side effect of also performing a detailed worst case circuit analysis by a highly-skilled analyst (e.g., Terry Flanagan/IRT, Dave Swant/GE for GPS clocks). Modern circuit analysis tools are remarkably effective. That modeling relates closely to initial and end of life (EOL) performance margins. Furthermore, this information is important for verifying component stress levels and making reliability predictions.

[78] GPS clocks are hand made by dedicated craftspersons whose workmanship, more than anything else, is responsible for their excellent reliability. Each clock is individually observed and adjusted during testing to perform the best it can.

[79] Excerpt frpm *GPS World* 4/26/17: "GPS III Rubidium Atomic Frequency Standards (RAFS) have evolved from GPS IIR and IIR-M RAFS, which have collectively and reliably provided more than 250 years of on-orbit service, including significant time beyond their intended design lives. Our GPS III RAFS clocks undergo rigorous environmental qualification and life tests to assure performance over this next generation satellite's 15-year design life. In addition, each GPS III SV includes multiple RAFS for redundancy. GPS III continually monitors the active RAFS to detect and mitigate clock anomalies. This is just one way that GPS III provides increased signal integrity for GPS users. Galileo clocks utilize different suppliers than GPS III clocks. The GPS III clock supplier has produced reliable RAFS clocks for GPS satellites over the past several decades."

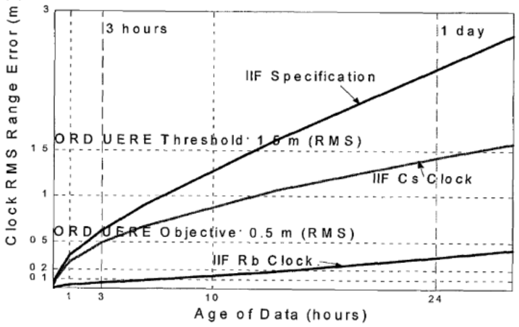

Fig. 39. Estimated GPS IIF Clock Range Error. Plot Credit: Wu & Feess, 2000 PTTI [170].

In preparation for GPS III, a program of further improvements called RAFSMOD was initiated in 2005, which resulted in even better stability, as shown in Fig. 40 where the flicker floor extends below $1x10^{-15}$ at averaging times longer than several days[80].

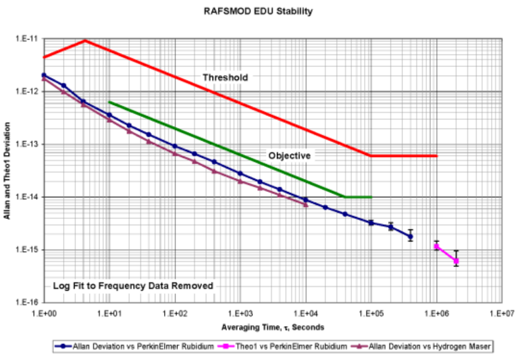

Fig. 40. Excelitas RAFSMOD EDU Stability. Credit: Dupuis, Lynch & Vaccaro, 2008 FCS [132].

The Excelitas GPS III RAFS displays exceptional stability, as shown in Fig. 41.

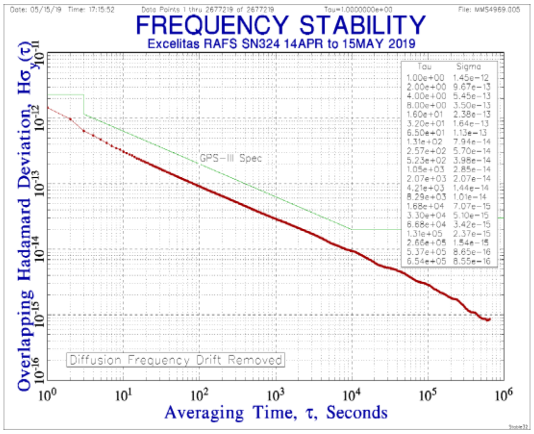

Fig. 41. Excelitas GPS III RAFS S/N 324 30-Day Drift-Removed ATP HDEV Stability Plot. This GPS RAFS reaches the $pp10^{16}$ range for $\tau \geq 5$ days and has a modeled white FM noise level of only about $1x10^{-12}\tau^{-1/2}$ which corresponds to a time deviation of only about 0.1 ns at 1 day. Plot Plot Credit: Excelitas.

4) *EG&G GPS RAFS Aging*

Mature GPS RAFS units show aging in the low pp1014/day range. Where effective measures are taken to minimize light shift and other factors, the most important contributor to aging is likely diffusion of absorption cell N_2 buffer gas into the glass envelope and/or Rb surface film. This theory is supported by their consistent negative aging direction and excellent fit to a diffusion (√t) law, as shown in Fig. 42 [231]. RFS aging references herein are [230] through [233].

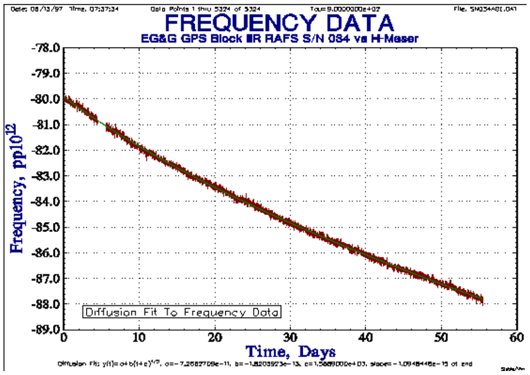

Fig. 42. RAFS Aging Plot with Diffusion Law Fit. Plot Credit: EG&G.

5) *EG&G Military RFS*

As the EG&G GPS Rb clock design was progressing, the same group developed a small, ruggedized unit directed at military applications. That effort was driven by competitive U.S. Air Force RADC programs at EG&G, Efratom, and Litton to develop a tactical RFS (TRFS) for the Hazeltine Seek-Talk anti-jam radios[81]. The main challenge was a very severe operating environment that included fast warm-up, mechanical vibration and high temperatures. All three organizations successfully built prototype units with EG&G and Efratom gaining new core products[82, 83] and Litton launching a new technological base that was later sold to FEI. References herein to MIL/tactical RFS history are [141] through [155].

6) *The EG&G TRFS*

The EG&G TRFS (and similar units from Efratom and Litton, later FEI, see Fig. 48) were the most rugged tactical RFS units ever made. Although the Seek-Talk radios were never produced, the concepts learned were utilized later in the EG&G RFS-10 family (see Figs 43 and 44). References to RADC Technical Reports and papers re these tactical RFS units for

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[80] PerkinElmer received a contract in June 2009 for RAFS for the 1st two GPS III spacecraft, "Having built more than 100 atomic clocks for space, far exceeding that of any other company, we are confident that our dedicated design and manufacturing capabilities and 30 years of experience will serve to enhance GPS satellites for decades to come," said John Vaccaro, Technical Director of RAFS at PerkinElmer.

[81] The overseers of the three TRFS contracts at RADC were Nick Yanoni, Al Kahan and Ferdy Euler (the latter for EG&G). Although little came of the Seek-Talk radio program, the TRFS work had important effects on the three contractors. Efratom got a new product (the M-1000 evolved into the M-3000 with improved reliability). Litton got a new technology, which they soon sold to FEI. EG&G got an entry into the military RFS business to supplement their GPS Rb clock work.

[82] The EG&G TRFS and Efratom M-1000.

[83] Management seems to always push end-of-the-year sales. I delivered a critical contractual milestone test report on the TRFS to Ferdie Euler (along with a box of wine) at the gate of Hanscom AFB on New Year's Eve in 1982.

the three participants will be found in References [146] through [154].

7) *The EG&G RFS-10*

The EG&G RFS-10 was designed as an equivalent to the Efratom M-100 MIL RFS in a smaller package. However that turned out to be a marketing mistake as the larger M-100 format had become an industry standard of sorts, especially in military procurements where multiple sources were encouraged. Thus most RFS-10 sales were for units where the smaller RFS-10 core was put into a larger package. In later years, the smaller size became more widely used, was duplicated by a Symmetricom M-100 replacement (see Fig. 50), and continued to be produced well into the 2000's.

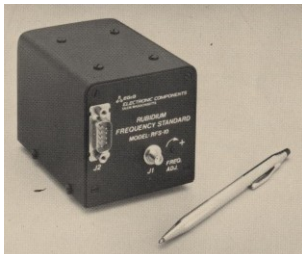

Fig. 43. EG&G RFS-10. Photo Credit: EG&G.

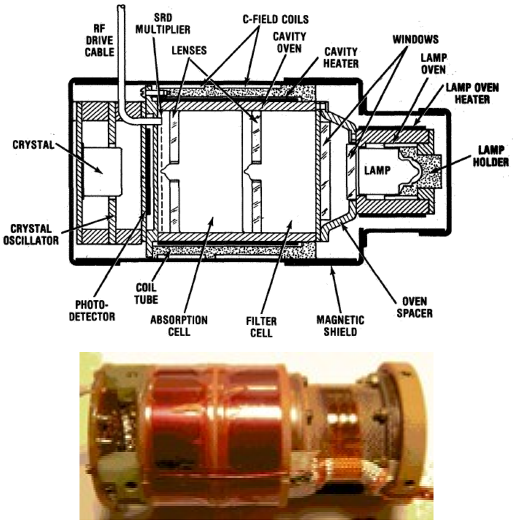

Fig. 44. Seek-Talk Rb Physics Package. The EG&G Seek-Talk Rb physics package utilized a discrete filter cell co-located in the microwave cavity/oven with the absorption cell[84]. The crystal oscillator shared the same thermal environment. It was rigidly attached to the Rb lamp assembly. See U.S. Patent 4,494,085. Figure Credit: EG&G.

Thus the largest number of EG&G military RFS units were RFS-10-7 equivalents to the Efratom M-100 (see below), which were used in considerable quantities in such programs as the Raytheon TRC-170 troposcatter radio and the Magnavox Have-Quick aircraft radios[85].

8) *The EG&G RFS-10-7 and RFS-10-102*

The EG&G RFS-10-7 and RFS-10-102 were versions of the RFS-10 in a larger box compatible with the popular Efratom M-100 militarized Rb frequency standard. One application for these units was the 1976-1995 Raytheon (Wayland and Bedford, MA), and Unisys (Salt Lake City, UT) 2nd source U.S. Air Force AN/TRC-170 troposcatter radio. Although its procurement ended in 1995, as of 2017 this radio system was still in use.

Military anti-jam frequency hopping HF radios were another common RFS application during the 1980's, and there was stiff competition between EG&G and Efratom for that business. One such program was the 1983-1992 Magnavox (Ft. Wayne, IN) AN/TRC-179 Regency Net U.S. Army HF frequency hopping radios, with most RFS procurement circa 1986[86].

Other users of the RFS-10-7 were GTE Sylvania Communications Systems Division in Tauton, MA and Brandywine Communications.

References to RFS-10-7 and RFS-10-102 Technical Reports will be found in [141] through [143].

9) *The EG&G RbXO*

The RbXO (see Fig. 45) is a simple concept whereby a continuously-running crystal oscillator is occasionally syntonized by a rubidium reference. The idea is to save power (really energy) in a timing application by activating the Rb reference only as needed to maintain XO accuracy. This arrangement, championed by John Vig, makes most sense when a very low power ovenized crystal oscillator is used, and he oversaw a parallel program at Bendix and then Piezo Crystal for the Tactical Miniature Crystal Oscillator (TMXO)[87].

EG&G and Efratom had RbXO contracts with the U.S. Army, but only EG&G successfully completed the work. The challenge was mainly to develop an Rb reference that could quickly warm-up and syntonize the OCVCXO reliability thousands of time with minimal energy consumption[88].

Fig. 45. EG&G RbXO with TMXO (left). Photo Credit: EG&G.

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[84] There is a pitfall associated with placing the filter cell inside the microwave cavity. If it contains any Rb-87 there can be a spurious resonance at a frequency determined by the filter cell buffer gas.

[85] As I recall, in the largest single order for several hundred units, the procuring office made a mistake on the quantity; the excess units are probably still in some huge Government warehouse next to the Ark of the Covenant.

[86] Mal Schwalje was the sales manager for Rb products at EG&G in Salem, MA, and his standing joke was things were so tight that he had to take the bus to Ft. Wayne, IN. EG&G never achieved much success in the commercial RFS business and, at best, shared less than half the military business with Efratom.

[87] The TMXO per se never became a product, but to some extent led to the many very low power OCVCXO's available today.

[88] On-off power cycling endurance, especially at low temperatures with fast warm-up, is a difficult design challenge but essential to the RbXO concept. The EG&G RbXO was able to pass a tough design verification test (DVT) but a competitive unit was not. The DVT subjected 4 RbXO units to 180 days of -62°C to +68°C temperature cycling with 20 on-off power cycles per day.

Later, another program (circa 1985) called Modular Intelligent Frequency, Time and Time Interval (MIFTI) utilized the EG&G RbXO along with a microcontroller (with algorithms from Sam Stein of Timing Solutions) to discipline the system time and frequency. That work was a bit ahead of its time and was never completed[89, 90, 91]. But before long, there appeared a "Smart Clock" from HP and then a host of GPS-based disciplined OCVCXO and Rb products (although those did not emphasize low power).

Figure 46 shows an RbXO temperature/power cycling retrace characteristic as a function of air temperature with distinct hysteresis versus the direction of the temperature change. The RbXO would follow this characteristic over and over again during successive power and temperature cycles. RbXO references herein are [156] through [159].

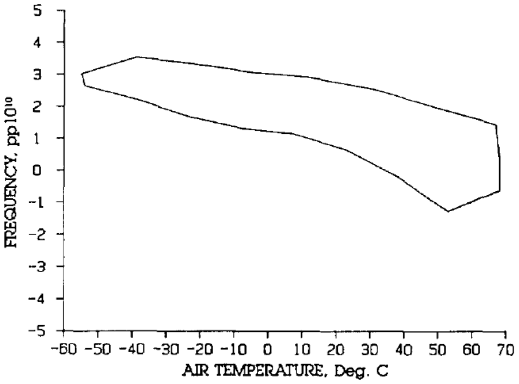

Fig. 46. RbXO Retrace Characteristic [210]. Plot Credit: EG&G.

10) *The EG&G SCOTT RFS-20*

The EG&G RFS-20 was an RbXO intended for use in the U.S. Army TSC-124 Single Channel Objective Tactical Terminal (SCOTT) EHF MILSTAR ground terminal, a circa 1985-1990 Magnavox (Ashburn, VA) program initiated at MIT Lincoln Lab in 1982. The RFS-20 was designed as the timing and frequency reference, with precise timing maintained for 10 days at low power during transport[92]. Based on the RFS-10, it was a very attractive design, but unfortunately the SCOTT program was terminated in 1993 before any production. References to the SCOTT program and RFS-20 Technical Reports will be found in [144].

E. Efratom/Ball/Datum/Symmetricom/Microsemi/Microchip

Efratom was founded in Munich Germany in 1971 by Ernst Jechart (along with Gerhard Hübner)[93] after his working on rubidium frequency standards at Rohde & Schwarz. Efratom developed and produced small RFS units (FRK, M-100, etc.) employing a then-innovative integrated resonance cell. The company expanded to Irvine, CA in 1973 where it became the largest manufacturer of RFS. It became part of Ball Corporation in 1982, Datum in 1995, then Symmetricom in 2002 (and moved to Beverly, MA), Microsemi in 2013, and then Microchip Technology in 2018.

Major contributors at Efratom included president Hugo Fruehauf, physicist Tom English, engineer Werner Weideman (see Fig. 53) plus engineers Bill Cashin and Jeff Crockett and physicist Jin Deng.

Noteworthy accomplishments included the first atomic clock in space (a modified FRK on NTS-1), the 1st generation Rb physics packages for GPS, rugged militarized units (M-00, M-1000, M-3000) and thousands of commercial RFS units (FRK, FRS, LPRO, X-72, etc.), see Figs 47-49 for examples.

Fig. 47. Efratom FRK Commercial RFS. Quoting from the Smithsonian National Museum of American History web site for this item: "This compact rubidium frequency standard is the commercial Model FRK, first made by Efratom Elektronik, Munich, Germany, and later by Efratom California in Irvine, Ca. Gerhard Hübner and Ernst Jechart established the firm in 1971 and a year later supplied examples of the clock to the Naval Research Laboratory (NRL), Washington, D.C., for inclusion on NTS-1, the first of the Navigation Technology Satellites (NTS) launched in 1974 to validate the key concepts and hardware for the Global Positioning System (GPS). Relatively large rubidium frequency standards had been developed in the 1950s, but the FRK—weighing roughly three pounds and measuring about four inches on a side—were the smallest atomic frequency standard of any type available. Efratom established a branch in Irvine, California, in 1973 and manufactured compact rubidium frequency standards there for a variety of customers. The firm became a division of Ball Aerospace in 1982 and then part of Datum in 1995. Symmetricom acquired Datum in 2002." Photo Credit: Ball Efratom (More photos on the Smithsonian web site).

Fig. 48. Efratom M-1000 Tactical RFS. Photo Credit: Ball Efratom.

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[89] Some of the ideas like taking advantage of environmental changes to learn OCVCXO compensation versus the Rb reference are still not commonplace.

[90] The RbXO was also a precursor to the U.S. Army SCOTT time and frequency reference (that was also never produced).

[91] A personal side benefit is that the author was exposed to the C programming language and PC programming in general, which led to other productive results.

[92] An RbXO depends on having a low power OCXO. Bendix and Piezo Technology were unable to successfully produce the U.S. Army TMXO needed for the SCOTT RFS. Sy Goldberg and Tom Lynch were granted U.S. Patent 4,845,337 for a novel low power ovenized crystal oscillator assembly. Efratom developed their EMXO as a low power OCVCXO.

[93] Jechart came to the U.S. in 1973 and Huebner remained in Munich to run the business there.

Fig. 49. Datum LPRO RFS. Photo Credits: Datum.

The Symmetricom 8130A (Fig. 50) was designed circa 2002 as a modernized equivalent to the Efratom M-100 with the smaller size of the EG&G RFS-10 (see Fig. 50). M-100 era tactical RFS units used MIL-spec parts that were increasingly hard to obtain, while modern electronic parts had achieved comparable reliability and offered more functionality (e.g., DDS synthesis). The semiconductors in the 8130A were, however, subjected to a custom screening process. Even that is seldom required for today's military RFS applications where commercial units have been successfully adapted for use in harsh environments[94].

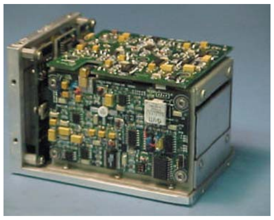


Fig. 50 Symmetricom Model 8130A RFS. Photo Credit: Symmetricom.

The Symmetricom X72 is a very small RFS for commercial telecom applications (see Fig. 51). It uses a conventional Rb lamp and a tiny cell inside a unique microwave resonator invented by Jinquan Deng [178].

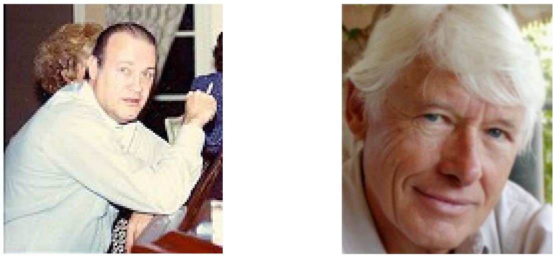
Fig. 51. Symmetricom X72 RFS. Photo Credit: Symmetricom.

More recently, Symmetricom has designed and manufactured RFS modules for the F-22 and F-35 aircraft based on the X72, as shown in Fig. 52.

As of 1993, more than 35,000 Efratom rubidium oscillators had been made for applications such as commercial and military communications systems, navigation systems, and metrology. By 1996, annual production exceeded 100k units, mainly for telecom applications, and there are now more than a half-million units in use.

Fig. 52. Symmetricom 8122 RFS Module. Photo Credit: Symmetricom.

An Efratom FRK rubidium oscillator was part of the atomic clock exhibit at the Smithsonian Institution in Washington, DC between 1982-1988. Two FRK units flew on the NRL NTS-1 spacecraft, becoming the first atomic clocks in space. Efratom supplied rubidium physics packages to Rockwell for use on the Blocks I, II and IIA GPS navigation satellites[95], and for a rubidium oscillator that was on the Huygens probe that landed on Saturn's moon Titan in 2005 [137].



Ernst Jechart (1936-1991)
Co-Founder of Efratom
Photo Credit: *GPS World.*

Hugo Fruehauf
President of Efratom
Photo Credit: *GPS World.*

Werner Weidemann (1943-2008)
Photo Credit: IEEE UFFC.

Tom English
Photo Credit: Logos Research.

Fig. 53. Major Efratom RFS Contributors.

Hugo Fruehauf, the president at Efratom during most of its time in Irvine, CA, came from Rockwell when they began to use the Efratom Rb technology for their GPS satellite program.[96] He was a charismatic leader with the highest professional and personal standards.[97] Later, he went to work for FEI and is now a consultant.

F. Litton

Litton Guidance & Control Systems in Woodland Hills, CA entered the field of Rb frequency standard technology as an adjunct of their work on rubidium NMR gyros in response to a 1983 USAF RADC contract for a tactical RFS (in which

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[94] The Symmetricom 8130A MIL RFS was a nice design, especially the low phase noise version, but reached the market too late to have any impact. Besides the author, its designers were Ken Lyon and Larry Zanca,

[95] There were a total of 17 Rockwell/Efratom RFS on the 11 Block I GPS S/Vs.

[96] Hugo relates a story about the U.S. Government threatening to shut down the GPS RFS work and deport Jechart because he was not a citizen.

[97] He received the 2019 Queen Elizabeth Prize for Engineering.

EG&G and Efratom also participated separately). We at EG&G were fascinated to follow their (public) reports as they independently and quickly rediscovered the basics of RFS physics. The principal contributors to the Litton work were Tae Kwon[98], Tom McClellan and Bruce Grover [149]. The Litton RFS technology was sold to Frequency Electronics in or about 1985.

G. Frequency Electronics

Frequency Electronics (FEI) was founded by Martin Bloch in 1962, and has become a major player in the T&F field, especially for ultrastable space crystal oscillators and custom designs for Government programs. It enjoys a good reputation for delivering promised performance, and Marty Bloch grew FEI into a very successful company[99]. Frequency Electronics acquired the Litton Rb technology in circa 1985, and Tae Kwon and Tom McClelland went to FEI in Mitchell Field, NY. Figure 54 shows the two major RFS contributors at FEI.

Martin Bloch
Photo Credit: ION.

Tom McClellan
Photo Credit: LinkedIn.

Fig. 54. Major FEI RFS Contributors.

FEI utilized that technology in an RFS subsystem for the MILSTAR and Advanced EHF communications satellites (see Fig. 55), and later for several commercial RFS products and also a 2nd source Rb clock for GPS. 19 FEI MILSTAR Rb systems were delivered as of 2004. Examples of FEI commercial RFS products are shown in Figs 56 and 57. The FE-5650A was used in Lucent cell phone towers.

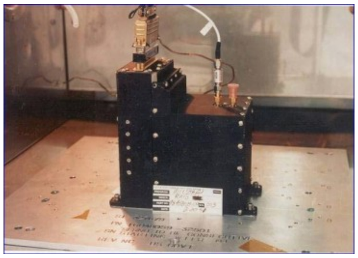

Fig. 55. FEI MILSTAR Rubidium Master Oscillator. Photo Credit: Frequency Electronics.

Fig. 56. FEI FE-5680A Commercial Telecom RFS. Photo Credit: Frequency Electronics.

Fig. 57. FEI FE-5680A Commercial Telecom RFS. Photo Credit: Frequency Electronics.

H. AccuBeat

AccuBeat is a relatively small but well-established company in Israel founded by Avi Stern that designs and manufacturers time and frequency products including rubidium frequency standards. AccuBeat predecessors include FEI, Tadiran and Time & Frequency, Ltd. (TFL, e.g., the TF-4000, TF-4020 and TF-4030 RFS). Some of its products have been sold through PerkinElmer/Excelitas in the U.S., and apparently they now partner with Bliley. An AccuBeat commercial RFS is shown in Fig. 58.

Fig. 58. AccuBeat AR40A RFS. Photo Credit: AccuBeat.

I. Stanford Research Systems

Stanford Research Systems (SRS) has an interesting and diverse product line that includes rubidium frequency standards and related instruments (e.g., the SRS620 counter, for which it was designed as a time base). Their PRS10 Rubidium Oscillator (see Fig. 59) has good specifications and a reputation for excellent performance. It utilizes a low noise OCVCXO, a lamp with a large Rb reservoir, digital control, and sinewave servo modulation.

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[98] Tae Kwon left Efratom in 1978 to join Litton.

[99] FEI encountered legal problems when it was suspended from eligibility for U.S. Government prime contracts in December 1993 based on an indictment of four of its officers for conspiracy to defraud the Government. That suspension lasted through June 1998, when the charges were dismissed.

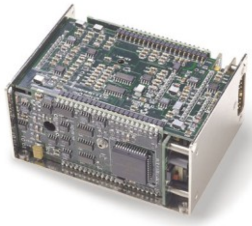

Fig. 59. Stanford Research PRS-10 RFS. Photo Credit: Stanford Research Systems.

The PRS10 includes hardware and firmware that allows it to be locked to an external 1 PPS signal from, for example, a GPS timing receiver, as shown in Fig. 60. The principal designer of the PRS-10 was John Willison.

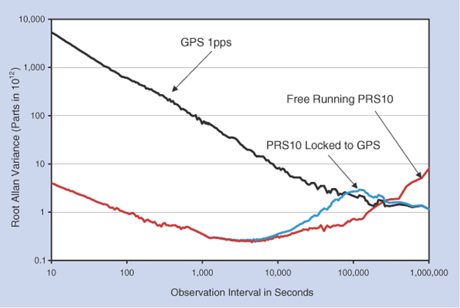

Fig. 60. PRS-10 ADEV Plot with 1 PPS Reference. Photo Credit: Stanford Research Systems.

J. Quartzlock

Quartzlock in the UK has offered rubidium frequency standards as part of its product line for quite some time (e.g., circa 1986 or earlier). These units were apparently first associated with Dartington Frequency Standards (also located in Devon, UK). The Quartzlock A10 Bench RFS (see Fig. 61) data sheet of 2002 includes a brief RFS history [79]. Quartzlock also developed (circa 2015) an E10-SPC space qualified Rb clock.

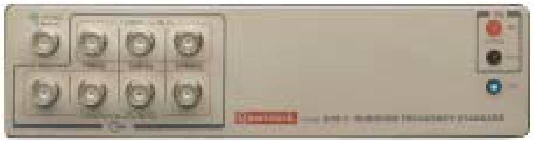

Fig. 61. Quartzlock A10 Bench RFS. Photo Credit: Quartzlock.

K. Small Companies

It has always been difficult for a small startup company to succeed in the RFS business. The technology is fairly complex and customers tend to be large organizations that expect in-depth support.

Aqtron was a small company that briefly manufactured and sold rubidium frequency standards circa 1982. It was owned by William R. Fowks who had previously worked on those devices at Rockwell.

CJI Technology was another name from the past. IQD is a current RFS name in the UK.

L. U.S. Government

The U.S. Government has played a significant role in the development of rubidium frequency standard technology.

At the beginning, the National Bureau of Standards (NBS, now NIST) and the Naval Research Laboratory (NRL) were involved in the applied research that led to RFS instruments. They have continued to stay involved, with NIST recently doing early work on the Chip Scale Atomic Clocks (CSAC) and NRL serving as a ground life test facility for GPS Rb clocks [130]. The U.S. Naval Observatory continues to closely monitor those clocks in-orbit. The U.S. Army supported several RFS-related programs (e.g., RbXO, MIFTTI, SCOTT) during the time Ft. Monmouth was still open. The U.S. Air Force has, in the past, supported several tactical communications programs that employ RFS units (e.g., Have-Quick, Seek-Talk, TRC-170), and it, of course has the major role in the GPS program. NASA has occasionally supported RFS work (e.g., SATS) and continues to support the JPL efforts on the Deep Space Atomic Clock (DSAC) Hg ion clock which has some similarities to an RFS[100].

The quasi-government Aerospace Corporation has played a significant role in RFS research and has provided important support to the MILSTAR and GPS programs.

M. International Organizations

Several private and governmental organizations are active in rubidium frequency standard technology outside the United States. The former manufacture a line of RFS products while the latter are mainly associated with GNSS applications.

N. Switzerland

The atomic clock activity in Switzerland has been centered at the Neuchâtel Observatory and various companies located there.

1) Orolia

Orolia has a product line that includes commercial and space rubidium frequency standards (see Fig. 62). Spectracom and SpectraTime (previously Temex Neuchâtel Time – founded in 1995 - and Temex Time) are Orolia subsidiaries. Their principal technologist is Pascal Rochat, managing director of SpectraTime, Inc.

Orolia built the RAFS for the both the Galileo and Indian IRNSS navigation satellites, which have both experienced early in-orbit failures due to a “faulty component”, a problem now believed to be resolved. These Rb clocks may also have been used by China in the BeiDou GNSS system. Their stability (see Fig. 63), although excellent, is not quite as good as the Excelitas GPS RAFS (see Figs 40 and 41).

Fig. 62. Orolia LPFRS and Galileo RAFS. PhotoCredit: Orolia.

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[100] A DSAC demonstrator unit was launched in June 2019.

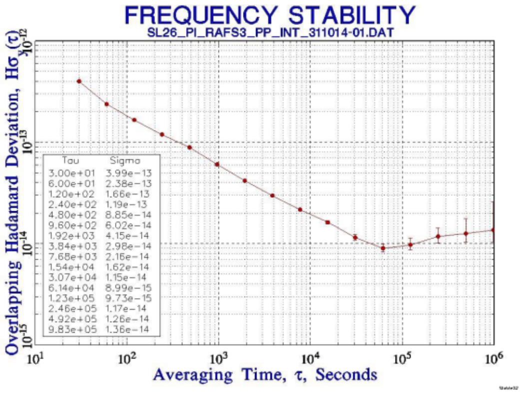

Fig. 63. Typical Stability of Galileo RAFS. Plot Credit: Spectratime.

O. *Japan*

Japan has had for many years indigenous RFS technology that has been applied mainly by telecom companies for internal use. RFS manufacturers have included Fujitsu, Nippon Electric Company (NEC, e.g., Neatomic Rb-1003) and Japan Radio Company (JRC).

The Japanese Quasi-Zenith Satellite System (QZSS) is a communication, broadcasting and positioning satellite system that offers a complementary service for GPS. It uses an Excelitas Rb clock similar to that of GPS-IIF [139].

P. *Russia*

In general, I know little about Russian RFS technology and products, but they have a long history with Rb, Cs and H-maser atomic clock technology.

The Russian Global Navigation Satellite System (GLONASS) space vehicles use a mixture of Russian-made Rb and Cs atomic clocks [139].

There also appear to be Russian manufacturers of small commercial RFS units, including Ruknar, which was founded in 1997 (see Fig. 64).

Fig. 64. Ruknar CH1-1012 RFS. Photo Credit: Ruknar JSC .

Q. *China*

Little general information is known about Chinese RFS technology and products.

Chengdu Spaceon Electronics Co., Ltd. offers RFS products, as may the China Aerospace Science and Industry Company (CASIC).

Rb clocks are used onboard the BeiDou GNSS system [139]. In late 2018, the BeiDou-2 constellation consisted of 14 active satellites all of which use Rb clocks. Per a 2018 paper, the stability of the improved Rb AFS on BeiDou-3 is comparable to that of the Galileo RAFS [138].

R. *India*

India has recently developed an indigenous Rb clock for their Indian Regional Navigation Satellite System (IRNSS). It may use either an Rb clock from SpectraTime or one developed locally. Information about the latter will be found in Reference [140].

S. *Italy and France*

The French telecom company Thomson-CSF (now Thales) made a HAM-111 laboratory RFS in the early 1970's. Most of the current atomic clock activity in these countries is research oriented at organizations such as IEN/INRIM and CNRS.

T. *Patents*

Patents have never been a significant factor in RFS commerce and very few have resulted in royalty payments[101]. Nevertheless, they can make for interesting reading (see patent references herein), and some are quite informative. Trade secret protection regarding Rb physics package processes is much more commonly used. Recent devices often contain firmware that is generally tightly controlled.

U. *RFS Formats*

RFS devices are available in a number of formats to serve a variety of applications:

- Components (e.g., CSAC – though mainly Cs)
- Boards (with CSAC or small RFS)
- Modules (most small RFS units)
- Black Boxes (military, avionics and aerospace units)
- Instruments (with power supply & controls)
- Systems (with time/frequency distribution, etc.)

Quite a few companies bundle RFS units into more complete assemblies and the core Rb manufacturer sometimes isn't clear.

V. *RFS Applications and Markets*

RFS applications gradually evolved from laboratory standards to military communications and avionics equipment and then to commercial telecommunications with yearly manufacturing volumes increasing from hundreds to tens of thousands, influenced greatly by the advent of GPS. The combination of a GPS time reference and a small Rb oscillator for short-term stability and holdover is essential to today's telecom networks. It's interesting that the trend toward smaller and lower cost RFS has been accompanied by generally lower performance except for the GPS/GNSS clocks where performance has been significantly improved. One report puts the global RFS market at $130 million in 2019 with an annual growth rate of 6.8% and about half produced in the U.S.

Over the years, high-end RFS performance has improved remarkably by 2 to 3 order of magnitude with flicker floors

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[101] For example, Jechart's U.S Patents 3,798,565 and 3,903,481 on the integrated resonance cell and mixed lamp isotopes for light shift reduction did not bring in revenue as far as I know, nor did Goldberg's 4,494,085 which was infringed but never seriously enforced. The legal costs of enforcement are higher than any returns. Some, like Riley's 4,721,890 have been honored and worked around by competitors.

dropping from pp10^{11} to pp10^{14}. Similarly, RFS volumes have been reduced from the size of a microwave oven to a deck of cards, power has been reduces from 10's of watts to fractions thereof, and the cost of commercial units has gone from the price of a car to 5% of that.

W. Surplus RFS Units

Used RFS units, particularly Efratom LPROs (see Fig. 65), are currently available on the surplus market for around $250 or even less. These are apparently some of the thousands removed from telecon cell sites for preventive maintenance or technical obsolescence. Most still operate fine and have years of life left, and are used by radio amateurs and hobbyists, often with GPS disciplining. These days, there is little reason for anyone who needs or wants an atomic clock to not have one.

Fig. 65. Surplus Efratom LPRO RFS. Photo Credit: E-Bay.

X. GPS and RFS

It can be argued that GPS is the single most important thing affecting RFS usage since that system was invented. High performance Rb clocks have turned out to be the best match for the time reference requirements on board a GPS satellite thanks to their combination of short and medium term stability (out to several days) along with practical factors like size, weight, power and (especially) life and reliability. On the ground, the combination of a GPS reference and an inexpensive modest performance RFS provides an ideal time reference for telcom applications at thousands of cell sites. The fit between RFS capabilities and those market needs has resulted in Rb clocks with exceptional performance on one hand and remarkably low cost on the other.

Y. T&F Industry Business Relations

With very few exceptions, the author has found business relations within the time and frequency community to be cordial and collegial, even between competitors. Business is conducted fairly and information is shared quite freely, with an emphasis on program success by all participants. It is a diverse international group from academia, government, and industry. Personal friendships and organizational ties are fostered at meetings and conferences. Similarly, the metrology, military, telecom and aerospace customers for T&F products in government and industry are, almost without exception, knowledgeable, competent and a pleasure to deal with.

V. NEW TECHNOLOGIES

A. Analog to Digital

Even the earliest RFS units in the mid-1960's were solid state (except for the first lamp exciters which used vacuum tubes), but Rb frequency standards remained mostly analog devices until the mid-1990's. Discrete semiconductors were gradually replaced by ICs, and better devices (e.g., op amps) improved RFS performance and reliability. Some of today's designs have become largely digital, as DDS/PLL synthesizers enabled high-resolution tuning, perfect squarewave FM, selectable output frequency and eased absorption cell buffer gas fill tolerances. Microprocessors, DSP and firmware have enabled digital frequency lock servos, fast lock acquisition, better oven control[102], temperature compensation, C-field commutation, digital monitors, user interfaces, external locking and self-contained calibration, test and aging measurements.

B. New Technologies

The classic rubidium frequency standard hasn't changed drastically since its beginnings (see early patents), but rather has enjoyed gradual refinement including improved performance along with reduced size, weight, power and cost as advances have been made in their physics packages and electronics. In particular, digital synthesis and signal processing have replaced analog circuitry. The three most significant recent technical innovations, laser pumping, CPT interrogation and MEMS micro-fabricated physics packages, are based on the availability of semiconductor diode lasers.

1) Diode Laser Optical Pumping Source

Replacing the conventional Rb spectral lamp and lamp exciter (and eliminating the Rb-85 isotopic filter cell) with a single mode diode laser (e.g., VCSEL, DBR or ECL) with its current source (and likely a cooler/temperature controller) is a potentially attractive choice for an RFS optical pumping source that offers more efficient pumping, a larger signal and higher S/N ratio. The main challenges are laser noise, wavelength/light shift control, and device availability and reliability. This approach has been applied to high performance units with complex laser systems that have achieved order-of-magnitude better short term stability, to small Rb and Cs devices using conventional microwave interrogation, and to small RFS units using CPT interrogation.

The evolution of ultra-miniature gas cell physics packages arguably began with a laser-pumped Cs device using a very small 0.2 cm^3 cell in a heavily dielectrically loaded cavity at Westinghouse (later Northrop-Grumman) in the early 1990's by P. J. Chantry, I. Liberman, et al., see Figure 66 [194], [296], [297].

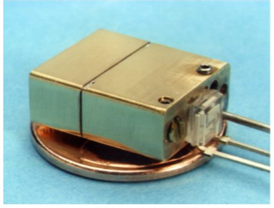

Fig. 66.
Ultra-Miniature Cs Resonator
Photo Credit: Northrop-Grumman

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[102] For example, digital oven controllers use A/D and D/A converters and DSP between their thermistor sensors and power transistors (instead of just a wire) but gain programmable set point and demand power along with improved control dynamics.

2) Coherent Population Trapping

Coherent population Trapping (CPT) is an alternative interrogation method that has been successfully used to implement both Rb and Cs gas cell atomic clocks[103, 104]. Its implementation uses wideband modulation of a VCSEL diode laser at one-half the atomic hyperfine frequency to excite the atoms in a gas cell with the resulting optical sidebands, thereby eliminating the need for a bulky microwave cavity.

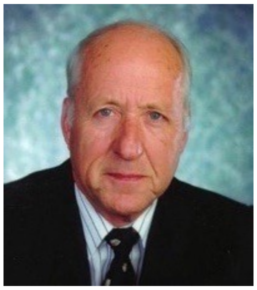

Fig. 67. Jacques Vanier. Photo Credit: IEEE

Jacques Vanier traces the history of CPT from the 1976 experimental work of Alzetto et al with sodium in [324] and the 1979 theory of Orriols in [325], later interpreted by him in [3] and [329]. The use of CPT in a frequency standard was proposed by Cyr, Têtu and Breton in [326] and followed up by Levi, Godone and Vanier in [327] and [328].

An early CPT clock was developed at Kernco in 2003 with ONR sponsorship[105]. CPT atomic clocks have found a substantial place in the atomic clock market for small, low power devices with modest performance (see Figs 68 and 69 for examples). References herein for CPT interrogation are [229] and [323] through [328]. A CPT clock is nicely described by Vanier in U.S. Patent 6 320 472 [323].

Fig. 68. Microsemi SA.3Xm CPT Rb Miniature Atomic Clock. Reference [229] gives an excellent description of a small, low power Rb clock (the Symmetricom, now Microsemi SA.3Xm) employing CPT interrogation. This technique provides performance equivalent to a conventional RFS unit in a much smaller package, and seems to represent the future of those devices. Photo Credit: Microsemi.

Fig. 69. AccuBeat NAC-1 CPT Rb Atomic Clock. Photo Credit: AccuBeat.

3) Chip Scale Atomic Clocks

The Chip Scale Atomic Clock (CSAC, see Figs 70 through 71) is a promising newer technology related to the RFS[106, 107, 108]. Although mainly using Cs rather than Rb gas cells, and generally having lower performance, a CSAC offers significantly smaller size, lower power and potentially lower cost than a traditional RFS.

A photograph of a 2004 NIST CSAC physics package is shown in Figure 69. The principal investigators for this work were John Kitching and Leo Hollberg with Svenja Knappe.

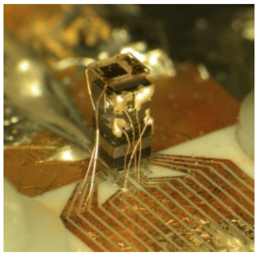

Figure 70. NIST CSAC Physics Package. Photo Credit: NIST

Quoting from NIST "The physics package of the NIST chip-scale atomic clock includes (from the bottom) a laser, a lens, an optical attenuator to reduce the laser power, a waveplate that changes the polarization of the light, a cell containing a vapor of cesium atoms, and (on top) a photodiode to detect the laser light transmitted through the cell. The tiny gold wires provide electrical connections to the electronics for the clock."

Commercial CSAC products are shown in Figs. 71 and 72.

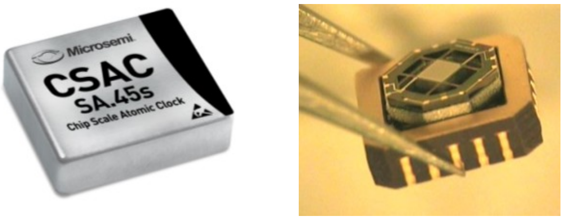

Fig. 71. Microsemi CSAC & Physics Package. Photo Credit: Microsemi. & Symmetricom.

Fig. 72. The Symmetricom CSAC is used in products made by Jackson Labs. Photo Credit: Jackson Labs.

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[103] CPT interrogation was first extensively investigated by Jacques Vanier.

[104] I recall sitting with Jacques Vanier in a Neuchâtel crêps shop during an EFTF conference as he tried to explain to me (without much success) CPT and quantum superposition states.

[105] Contributors at Kernco included Bob Kern, Marty Levine, Mike Delaney, Dan Janssen, and Cam Everson, with consultation by Jacques Vanier and Sy Goldberg.

[106] John Vig deserves much credit for spurring CSAC development by bringing together the MEMS and frequency control communities, followed by several DARPA-sponsored programs that led to the development of working devices by NIST, Symmetricom/Microsemi and others. Work by Jacques Vanier and others on CPT interrogation was an important precursor. At NIST, John Kitching showed theoretically that tiny gas cells can have usefully-small resonant linewidths. NIST pioneered the design and fabrication of CSAC cells and devices [Ref, Ref, Ref] At Symmetricom, the CSAC work was led by Mike Garvey, with Robert Lutwak devising the physics with electronics support by the author. Draper Labs MEMS technology was crucial, as were VCSEL devices from Sandia Labs.

[107] The majority of early CSAC devices have used Cs gas cells rather than Rb. At Symmetricom, this was somewhat due to familiarity with optically-pumped Cs beam tube technology, and with more readily available VCSELs at the Cs wavelength.

[108] CSAC devices are increasingly finding a place in the commercial atomic clock market, and low noise and rad-hard space versions are available. As of 2018, over 95,000 units had been sold by Microsemi [Ref].

The most important CSAC attribute is arguably its low power consumption compared with other atomic clocks as shown in Fig. 73. CSAC references herein are [220] through [228].

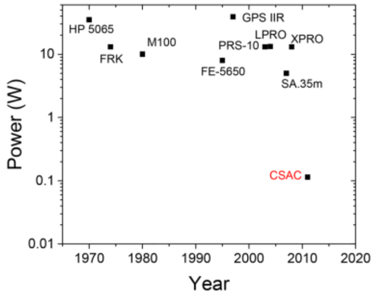

Fig. 73. Atomic Clock Power Consumption. Fig. Credit: J. Kitching [228]. Note: This is an excellent review of CSAC devices.

VI. COMMENTS AND CONCLUSIONS

A. Comments

It is quite remarkable that the three main atomic clock technologies today (Cs beam, Rb gas cell and H maser) remain basically the same as those in the 1960's. While there have been numerous additions to the types of laboratory/primary standards, few fundamentally new types of commercial atomic clocks have found acceptance, only variants like CPT interrogation, laser pumping and CSAC fabrication.

Also noteworthy are (a) the huge number of medium-performance low-cost commercial Rb clocks that are utilized by the telecommunications industry, (b) the exceptionally high performance and reliability that has been achieved by the GPS Rb clocks, and (c) the general improvement in electronic component reliability that allows use of commercial Rb designs in rugged military environments.

B. Conclusions

The rubidium frequency standard has been remarkably successful and can be expected to continue to serve as the most widely used atomic clock. Change comes slowly to this field, but it likely that small laser-pumped, CPT-interrogated units will become increasingly used. The originators of RFS technology are disappearing from the scene and one hopes that the next generation of atomic clock technologists will continue to follow with new ideas and accomplishments[109].

ACKNOWLEDGEMENTS

A. Credits

The figures herein without explicit credit are from the author's personal papers and archives, and/or Reference [5]. Product photographs are generally from their manufacturer's literature or web site. Thanks are due to the Princeton physics department for the picture of Tom Carver.

Several colleagues have reviewed and provided constructive comments about this history paper, including Peter Cash, Tom English, Hugo Fruehauf, John Kitching, Jacques Vanier and John Vig. I thank you all very much.

Rev. A of this paper mainly adds additional information about CPT compared with the original version of July 2019.

B. Professional Organizations

The three professional organizations listed below have provided for the exchange of information in the form of conferences, tutorials, standards and other committees and personal contacts within the time and frequency community:

- The IEEE Ultrasonics, Ferroelectrics and Frequency Control Society (UFFC) and the IEEE International Frequency Control Symposium (FCS). Access to abstracts from the annual FCS Proceedings is open, but UFFC membership or an IEEE Xplore subscription is required to obtain the full text.
- The annual Precise Time and Time Interval (PTTI) conference. An index to the full PTTI papers between 1969 and 2012 is available. After that, one must go to the Institute of Navigation (ION) web site, where membership is required for full paper download.
- The annual European Frequency and Time Forum (EFTF). Complete proceedings are available for free download since 1987.

Early RFS work was reported mainly at the FCS and the scientific literature. Later, FCS papers tend more toward devices and PTTI papers toward applications (e.g., GPS), while the EFTF emphasizes European work.

ABBREVIATIONS AND ACRONYMS

The following abbreviations and acronyms are used herein.

ADEV	Allan Deviation
AFB	Air Force Base
AFS	Atomic Frequency Standard
Ar	Argon
ATP	Acceptance Test Procedure
DBR	Distributed Bragg Reflector
BTC	Baseplate Temperature Controller
CAS	Collision Avoidance System
CMB	Cosmic Microwave Background
CNRS	National Center for Scientific Research (France)
CPT	Coherent Population Trapping
Cs	Cesium
CSAC	Chip Scale Atomic Clock
DARPA	Defense Advanced Research Projects Agency
DDS	Direct Digital Synthesizer
DSP	Digital Signal Processing
DSC	Differential Scanning Calorimeter
DSAC	Deep Space Atomic Clock
DVT	Design Verification Test
ECL	External Cavity Laser
EFTF	European Frequency and Time Forum
EG&G	Edgerton, Germeshausen and Grier
EHF	Extremely High Frequency
EMI	Electromagnetic Interference
ESS	Environmental Stress Screening
FCS	Frequency Control Symposium
FEI	Frequency Electronics Incorporated
FM	Frequency Modulation
FTS	Frequency and Time Systems
FXR	Flash X-Ray
GE	General Electric
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GR	General Radio, GenRad
H	Hydrogen
HDEV	Hadamard Deviation
He	Helium
HP	Hewlett Packard

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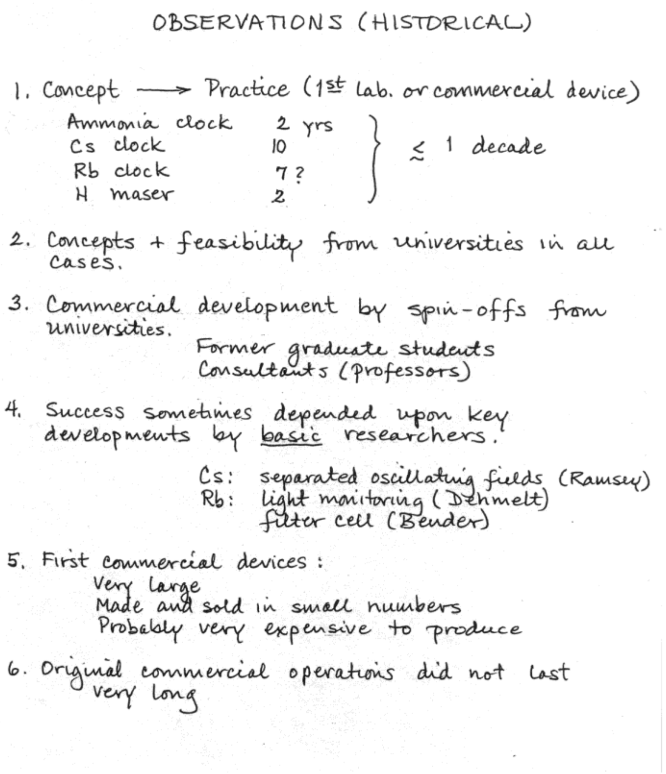
[109] The history of the rubidium gas cell atomic frequency standards extends back some 60 years. Looking forward, it seems clear that there will be a continuing need for precise time and frequency using these and similar devices.

IEEE	Institute of Electrical and Electronic Engineers
IEN	National Electrotechnical Institute (Italy)
INRIM	National Institute for Metrological Research (Italy)
IRNSS	Indian Regional Navigation Satellite System
I&M	Instrumentation & Measurement
ION	Institute of Navigation
IRE	Institute of Radio Engineers
ITT	International Telephone and Telegraph Company
JPL	Jet Propulsion Laboratory
JRC	Japan Radio Company
Kr	Krypton
LTE	Long-Term Evolution
MEMS	Micro Electro-Mechanical System
MIFTTI	Modular Intelligent Frequency Time Time Interval
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
NBS	National Bureau of Standards
Ne	Neon
NEC	Nippon Electric Company
NIST	National Institute of Standards and Technology
NMR	Nuclear Magnetic Resonance
NRL	Naval Research Laboratory
OCXO	Oven Controlled Crystal Oscillator
OCVCXO	Oven Controlled Voltage Controlled Crystal Oscillator
OMA	Optical Microwave Assembly
ONR	Office of Naval Research
PLL	Phase Locked Loop
PM	Phase Modulation
PTTI	Precise Time and Time Interval
QZSS	Quasi-Zenith Satellite System
RADC	Rome Air Development Center
RAFS	Rubidium Atomic Frequency Standard
R&S	Rohde & Schwartz
Rb	Rubidium
RbXO	Rubidium Crystal Oscillator
RFS	Rubidium Frequency Standard
SAO	Smithsonian Astrophysical Observatory
SATS	Spacecraft Atomic Timing System
SCI	Space Craft Incorporated
SCOTT	Single Channel Objective Tactical Terminal
S/N	Signal to Noise
SRD	Step Recovery Diode
STL	Space Technology Laboratories
S/V	Space Vehicle
SWP	Size, Weight and Power
TC	Temperature Coefficient
T&F	Time and Frequency
TMXO	Tactical Miniature Crystal Oscillator
TRFS	Tactical Rubidium Frequency Standard
TRW	Thompson Ramo Wooldridge
UFFC	Ultrasonics Ferroelectrics and Frequency Control
VCSEL	Vertical Cavity Surface Emitting Laser
VCXO	Voltage Controlled Crystal Oscillator
Xe	Xenon
XO	Crystal Oscillator

Historical Observations (by Tom English)



OBSERVATIONS (HISTORICAL)

1. Concept ⟶ Practice (1st lab. or commercial device)

Ammonia clock 2 yrs
Cs clock 10
Rb clock 7?
H maser 2
≤ 1 decade

2. Concepts + feasibility from universities in all cases.

3. Commercial development by spin-offs from universities.

Former graduate students
Consultants (professors)

4. Success sometimes depended upon key developments by basic researchers.

Cs: separated oscillating fields (Ramsey)
Rb: light monitoring (Dehmelt)
filter cell (Bender)

5. First commercial devices:

Very large
Made and sold in small numbers
Probably very expensive to produce

6. Original commercial operations did not last very long

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