From: http://www.ieee-uffc.org/main/history.asp?file=norton#The%20Warner%20Resonator

Brief History of the Development of Ultra-Precise Oscillators for Ground and Space Applications

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Abstract

The evolution of today's ultra-precise oscillators will be presented beginning with their origins, which were directly related to the development of the 2.5- and 5-MHz AT-cut resonator, designed by Warner at Bell Laboratories in 1952 and the introduction of the first all-transistorized frequency standard by Sulzer Laboratories in 1958.

Ultra-precise oscillator performance is ultimately dominated by the quartz resonator, and quartz resonator performance has improved dramatically since the original Warner resonator design. The improvements were achieved by refinements to the initial Warner design and improved resonator fabrication techniques, the development of a new SC-cut resonator, and a new resonator design, the BVA. The size reduction of resonators and the ability of the resonators to survive harsh environments has allowed the size of ultra-precise oscillators to be greatly reduced while still retaining excellent frequency stability. The relationship between resonator development and oscillator development is presented.

Ultra-precise quartz oscillators have demonstrated 24-hour aging rates of <1 X 10^{-12} and Allan variances of <6 X 10^{-14} at 10 and 100s. Oscillators with a £ *(f)* phase noise floor of <–175 dBc and <-135 dBc 1 Hz from the carrier have been reported. Environmentally induced changes in the oscillator output frequency are as low as <1 X 10^{-12} per unit measure with the exception of acceleration and ionizing radiation. The physical parameters of ultra-precise oscillators have been reduced to a volume of <300 cm^3 and a mass of <300 g. DC input power for an ultra-precise oscillator can be <0.5 W at 25°C. All of these performance parameters probably cannot be achieved in one oscillator but many of them can, and the performance parameters illustrate the capability of today’s oscillators.

Introduction

Frequency stability of ultra-precise oscillators has improved dramatically since the development of the Warner resonator in 1952. Development at Bell Telephone Laboratories in two areas, quartz resonators and the transistor, made possible the beginning of the modern era in quartz-resonator-controlled frequency standards in 1958. Evolutionary improvements in both resonators and oscillators were achieved in small steps at a slow pace until the revolutionary design of the SC-cut resonator and the BVA resonator produced step functions in ultra-precise oscillator performance.

The space age began in 1957 with the launch of Sputnik. Since then, ultra-precise oscillators have found use in a wide variety of spacecraft applications. Large numbers of oscillators have been used for some form of navigation beginning with the Navy Navigation Satellite System and continuing today with the Global Positioning System. The number of ultra-precise quartz oscillators placed in orbit is somewhat uncertain in part because of the definition of an ultra-precise oscillator, but the number certainly exceeds 1500 and could be greater than 3000.

Considerable effort was devoted to ensuring the data in this paper are accurate; however, the paper is not intended to be inclusive of all oscillator developments over the 40-year period this paper covers. The intent of the paper is to be representative of the history and development of ultra-precise oscillators, not to present a complete history. Without doubt some important data may have been inadvertently omitted. Please accept the authors' apology for these omissions. The data used for this paper in most cases are the best available for a given type of resonator or oscillator obtained from published sources, provided by individuals, or from personal knowledge.

The Warner Resonator

The performance of ultra-precise oscillators is dominated by the quartz resonator. The potential performance of a quartz resonator will be approached with a good oscillator design but the performance of the resonator and oscillator circuit combination can never exceed the capability of the resonator. Therefore, the development of precision resonators and precision quartz oscillator circuits cannot be separated. The precision resonators we use today are directly traceable to quartz resonator research at Bell Telephone Laboratories in the 1940s [1], which continued into the 1960s. Arthur W. Warner published a paper in 1952 [2] describing the Warner resonator design. A partial list of the design objectives for the Warner resonator follows: (1) raise Q to 10^6 or more; (2) achieve an ultimate frequency stability of 5×10^{-10}/24 hours; (3) preserve established production techniques; (4) achieve a temperature coefficient of frequency less than 1×10^{-7}/° C; and (5) shorten as far as possible the initial aging period. Most of these design objectives were demonstrated by an AT-cut, 5-MHz, 5th overtone resonator with a plano-convex quartz plate in a HC6 metal enclosure. The unit had a Q of 2.6×10^6 and an aging rate of about 5×10^{-10}/24 hours two weeks after manufacture. Work continued on this basic resonator design [3-5]. Two 5th overtone resonator designs operating at 2.5 and 5.0 MHz and mounted in glass enclosures were the results of the work at Bell Laboratories.

Development of Ultra-precise Oscillators

The use of vacuum tubes placed limits on precise frequency standards because of their low reliability, large size, and high operating power. The Western Electric GS-60157 2.5-MHz oscillator exemplifies some of these problems. The primary specification for oscillators in the late 1950s and early 1960s was the 24-hour aging rate. The GS-60158 used a Warner-designed 2.5-MHz resonator and had a very respectable aging rate of 3.3×10^{-11}/24 hours and a temperature coefficient of $<1 \times 10^{-9}$/°C. The oscillator unit had a mass of 50 pounds and a volume of 4588 in^3, and required 50 W of DC power [6].

The discovery of the germanium transistor, again at Bell Telephone Laboratories, by John Bardeen and Walter Brattain in 1948 and the development of theory leading to the junction transistor by William Shockley in 1949 paved the way for dramatic changes in frequency standards and the development of the small, high-stability frequency standards we enjoy today.

First All-Transistor Ultra-precise Oscillator

As transistors became commercially available, they were incorporated into quartz oscillator designs. Peter G. Sulzer described a transistor frequency standard that achieved a frequency stability of 1.4×10^{-9}/24 hours using a 100-kHz, GT-cut resonator in 1953 [7] . In this article Sulzer discussed the various configurations for transistor oscillators that provided insight into his choice for the oscillator circuit for the first commercial all-transistorized frequency standard in 1958. The JK-Sulzer Frequency Standard Model FS-1100T was designed at Sulzer Laboratories and marketed by James Knight Company. The oscillator used a James Knight JK G-12-AS AT-cut, 1-MHz fundamental resonator in a modified Colpitts circuit that became one of the trademarks of Sulzer oscillators. Other designers of the era were using the Pierce oscillator circuit. Extensive use of negative feedback is used to establish and stabilize the gain of the amplifiers and the operating drive level of the quartz resonator. The FS-1100T had an aging rate of <5 X 10^{-10}/24 hours, a I-s stability of 2.2 X 10^{-11} RMS, and a temperature coefficient of ±2 X 10^{-11}/°C. The oscillator had a mass of 7 pounds, a volume of 315 in^3, and consumed only 2 W of DC power [8]. While the aging rate of the FS- 1100T was not as good as that of the WE GS-60157, largely due to the 1-MHz fundamental resonator, which was significantly inferior to the Warner 2.5-MHz, 5th overtone resonator, there were large reductions in mass, volume, and input power.

Commercial Development of the Warner Resonator

Extensive research and development on the Warner resonator design was conducted at Bell Laboratories, but there was not a commercial manufacturer of the resonators in 1958 [4]. Bliley Electric began development of both the 2.5-MHz and the 5-MHz Warner resonator design for commercial use in 1955 and 1956 [9], and the 5-MHz resonator became available in 1958 or 1959 [10] . The Warner resonator was the workhorse of frequency standards into the early 1970s, and the basic Warner design of the quartz resonator plate and mounting structures continues to be used today with little change. In 1960 commercial frequency standards manufactured by Sulzer Laboratories, Manson Laboratory, Borg, General Radio, and perhaps others became available using the Bliley BG61AH-5, 5-MHz, 5th overtone, AT-cut resonator, which was a mass-produced commercial version of the Warner resonator.

The Sulzer Oscillator

The performance of the Sulzer model 5A (1960) and model 2.5A (1962) oscillators was outstanding even by today's standards, and in the early 1960s they were the standard for performance. Many of the oscillator design principles required to obtain precise frequency control were incorporated into the Sulzer oscillators. These design ideas and how they contribute to setting of performance standards are discussed below. Maintaining a low, constant (±1 dB) resonator drive level (» 60 m A for a 5-MHz, 5th overtone, AT-cut resonator) is a primary requirement for a precision oscillator. To establish and maintain this drive level, a stable automatic gain circuit is necessary, and amplifiers used within the automatic gain circuit loop must have very stable gain. Sulzer oscillators had both AC and DC negative feedback around amplifier stages to stabilize the DC operating point and the AC gain and to reduce noise. The amplifiers included unbypassed emitter resistors to help stabilize amplifier gain and to increase the input impedance of the amplifier. Unbypassed emitter resistors were later found to be the only effective way to reduce flicker noise [11], but that was not the implicit reason they were used in the Sulzer oscillators. In a Colpitts oscillator circuit, one side of a network of passive components that sets the operating frequency of the quartz resonator is grounded, which helps to minimize noise in the oscillator and contributes to the oscillator' s high performance.

Stable and accurate temperature control is essential for precise frequency control. The design goals for an oscillator oven are very simple: set and maintain the operating temperature of the oven at the turning point temperature of the resonator at ±0.001° C, isolate the resonator and selected circuit components from ambient temperature changes, and minimize thermal gradients within the quartz resonator. Realizing these goals is not so simple, but the following design ideas contribute to achieving the goals. Make the oven walls thick to obtain high thermal capacity and low thermal resistance surrounding the resonator. Close thermal coupling between the heater windings and the temperature-sensing thermistor embedded in the oven wall is required to minimize the time between an ambient temperature change and the application of power to the heater that maintains the oven at its set temperature. Stable, high-gain oven control circuits complete the oven control loop in the proportional controlled oscillator oven. A high-quality, low-thermal-conductivity insulating system such as a Dewar vacuum flask provides thermal isolation from rapid temperature changes and allows the oven controller to respond more slowly and more accurately to the temperature change. The use of a Dewar also reduces the input power required to maintain the oven at elevated temperatures. All of these design features were incorporated into the Sulzer oscillators and contribute to their excellent performance [12].

The Sulzer 2.5A oscillator used a 2.5-MHz, 5th overtone resonator. One of these oscillators (serial number 6) was a working frequency standard at The Johns Hopkins University Applied Physics Laboratory (JHU/APL) in the early 1960s. It had an exceptional but not rare aging rate of less than 5 X 10^{-13}/24 hours. The Allan variance of a Sulzer 2.5A oscillator was recently measured, and results are shown in Table 1.

Many of the oscillator design principles employed by Sulzer were also incorporated into oscillators designed by Bell Telephone Laboratories [6, 13, 14]. The development of oscillators at both laboratories occurred in the same time frame, but the design principles were developed independently. The Bell reports were published after the original Sulzer design, and Sulzer did not have access to the activities at Bell during his design efforts.

Table 1. Oscillators with best Allan variance of the era.

Manufacturer	**Sulzer**	**JHU/APL**
Model	2.5A	Type 142
Output frequency, MHz	2.5	5
Allan deviation (tau), s		
1	5.70 X 10^{-12}	8.38 X 10^{-14}
10	6.10 X 10^{-13}	3 74 X 10^{-14}
100	2.90 X 10^{-13}	6.09 X 10^{-14}
Year	1962	1993

General Radio Oscillator

General Radio had a long history as a manufacturer of frequency standards. The type 1115-B was General Radio' s entry into the transistorized frequency standard market in the early 1960s. In Ref. 15, there is a discussion of spectral purity that comes very close to describing £*(f)* as we use it today. The noise floor of the 1115-B was – 146 dBc in a one-cycle bandwidth [15]. This performance was very good for that era.

Spacecraft Oscillators

With the launch of Sputnik on October 4, 1957, new applications for frequency standards arose. The exploration of space presented a new set of opportunities and challenges to resonator and oscillator designers. Size, mass, and power consumption either were not important or were secondary considerations for ground-based applications but are of the utmost importance in spacecraft applications. The harsh environment during the launch phase, especially the high vibration levels (which have the potential to destroy the quartz resonator), the temperature extremes, the presence of ionizing radiation, and the vacuum in the space environment present unique challenges to the oscillator designer. Reliability requirements for space-qualified oscillators severely limit parts selection, which constrains the oscillator design. An early space application for ultra-precise oscillators was navigation.

JHU/APL placed the first of a series of Navy Navigation Satellites, TRANSIT 2A, in orbit in 1960. The heart of this navigation system was a precision quartz oscillator that used a Bliley Electric BG73A, 3-MHz fundamental resonator. The oscillator had a daily aging rate of 8 X 10^{-9}. Data collected during a 15-minute satellite pass was used to compute a navigation fix. During a satellite pass, the oscillator output frequency changed less than 2 X 10^{-9}, permitting a determination of position to an accuracy of 100 m. To achieve this stability, the quartz resonator was cut to have a frequency slope of less than 5 X 10^{-8}/°C over a temperature range of 0 to 50°C. A large thermal mass and a very efficient multilayer insulating system were used to minimize temperature changes at the resonator during a satellite pass. These design options produced an oscillator with a mass of 8 pounds and a volume of 48 in^3, that required only 0.11 W of DC power [16, 17]. A photograph of this oscillator is shown in Fig. 1. An oscillator with reduced mass and improved frequency stability was developed by JHU/APL using a mercury thermostatic switch to control the temperature of the oscillator oven. This oscillator was flown in 1961 on the TRANSIT 4B spacecraft.

Oscillators from both Sulzer Laboratories and Frequency Electronics were placed in orbit in 1963. The Sulzer oscillator was used for a form of navigation. Timing pulses derived from the oscillator flashed a xenon strobe lamp, which was photographed against a star background to determine the position of the spacecraft. This oscillator had an aging rate of 1 X 10^{-10}/24 hours. The Frequency Electronics oscillator was used on the Nimbus spacecraft and had an aging rate of 1 X 10^{-9}/24 hours [18].

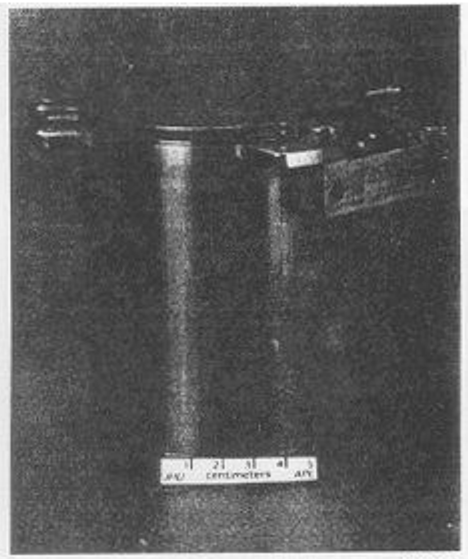

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Figure 1. One of the first ultra-precise quartz oscillators placed in orbit aboard the TRANSIT 2A spacecraft.

Figure 1. One of the first ultra-precise quartz oscillators placed in orbit aboard the TRANSIT 2A spacecraft.

New Enclosure for the Warner Resonator

Performance of the Warner resonator design continued to improve, by decreasing the initial aging period and reducing the aging rate. Many gradual improvements included better raw quartz material, improved cleaning techniques for the resonator parts, and cleaner oil-free vacuum systems used to evacuate the resonator enclosure [19]. The next improvement of commercially available resonators came with the introduction of the Bliley BG61AH-5S in 1968 [20]. The basic quartz blank was changed very little from the original Warner design, but there was a drastic change in the glass enclosure. The most obvious was a reduction by approximately 42% in length, and the internal resonator mounting structure was simplified. Less obvious changes were made in the processing of the resonator subassemblies, primarily to make and keep them cleaner. The net result of this work was a smaller resonator with improved frequency stability and the establishment of the aging rate in days rather than weeks or months. The shortened enclosure also permitted the size of oscillators to be reduced.

Frequency and Time Systems Spacecraft Oscillator

Frequency and Time Systems placed their first spacecraft oscillator (model 1251) in orbit in 1973 on the NST-2 Timation satellite. This oscillator used the new Bliley BG61AH-5S resonator and had an aging rate of <1 X 10^{-10}/24 hours. Additional data for this oscillator are shown in Table 2 [21].

Table 2

New JHU/APL Spacecraft Oscillator

In 1974 JHU/APL initiated a new oscillator design. This oscillator was a completely new design, with both a new mechanical configuration and a new electronic design. The oscillator circuit was very similar to the Sulzer model 1150, which at the time was the best available commercial component oscillator. The Sulzer design was adapted with the consent and help of Peter Sulzer. The oscillator and oven controller circuit was fabricated using surface mount components, and the new Bliley resonator was used to reduce the size of the oscillator [22] . This oscillator was the TIP design; its performance data are shown in Table 2.

Phase Noise Becomes Important

Phase noise was a term seldom used prior to the early 1970s and was rarely found in oscillator specifications. Fred Walls published a paper [23] that traces the development of low-phase noise devices in great detail. The following are examples of low-noise oscillators that represent a breakthrough in performance. In 1969 Peter Sulzer designed the Sulzer 1170 for a special application. The 1170 had excellent phase noise performance that was not matched for another 6 years. It had a phase noise £*(f)* of –110 dBc 1 Hz from the carrier and a noise floor £*(f)* of –160 dBc 10 kHz from the carrier. It had an aging rate of 5 X 10^{-10}/24 hours and used a 5-MHz, 5th overtone, AT-cut resonator. The next major improvement in oscillator phase noise performance was made by Charles Stone in 1975 with the Austron 1120S. This oscillator used a high resonator drive level to achieve a noise floor of –180 dBc at 1 kHz from the carrier. Because of the high resonator drive level, the aging rate was only 5 X 10^{-9}/24 hours. The phase noise performance for both the Sulzer and Stone oscillators is shown in Fig. 2.

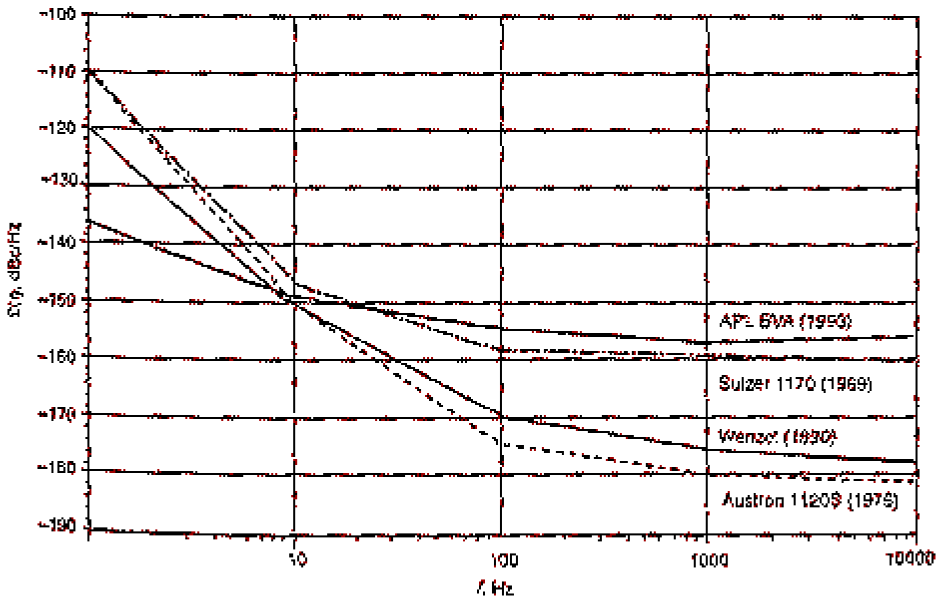

Figure 2. Phase noise of selected oscillators.

New Resonator Cut -The SC Cut

The most significant improvement in resonant technology since the Warner design was the prediction of a new resonator cut by Errol EerNisse in 1975 [24] and Jack Kusters in 1976 [25]. The new EerNisse resonator was named the stress compensated (SC) cut, and the Kusters resonator was called the thermal transient compensated cut (TTC) cut. Both resonators turned out to be the same cut, with the SC cut name gaining common use. The SC-cut has several advantages compared to the AT cut. (1) It has a much smaller temperature coefficient at the resonator turnover temperature; (2) the resonator can be operated at a higher drive level, which improves the signal-to-noise ratio and short-term frequency stability without degrading the aging rate; (3) activity dips that produce frequency discontinuities are rare in SC-cut resonators; (4) it has faster warmup with little frequency overshoot; and (5) it has lower acceleration sensitivity. The SC cut is a doubly rotated resonator and requires much tighter angular tolerances when the quartz blanks are cut from the quartz bar. The SC-cut resonator emerged from the development laboratories into commercial production around 1980. The use of SC-cut resonators in oscillators immediately improved their performance. A new oscillator design by Hewlett Packard, model 10811A/B, using an SC-cut resonator, was very similar physically to their model 10544B that used a AT-cut resonator. Figure 3a shows an obvious and dramatic decrease in temperature sensitivity and a significant improvement in the short-term frequency stability (Fig. 3b) [26].

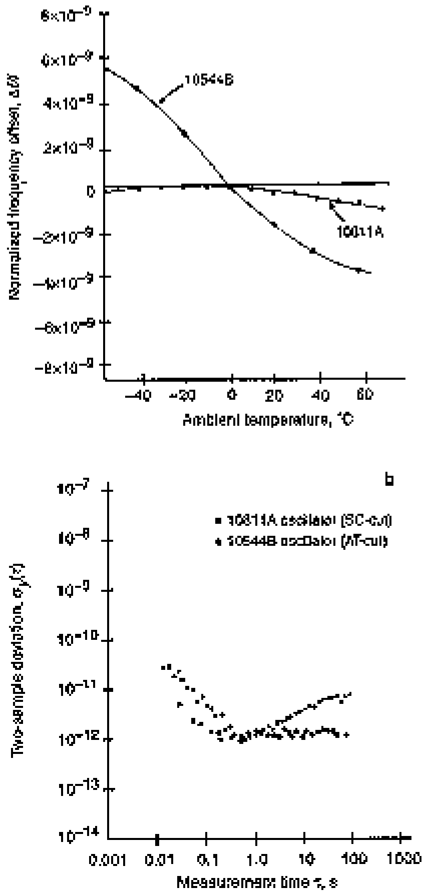

Figure 3. Effect of resonator cut on oscillator performance. (a) Effect on temperature sensitivity; (b) effect on short-term frequency stability. From Ref. 26. (C) Copyright 1981 Hewlett-Packard Company. Reproduced with permission.

Figure 3. Effect of resonator cut on oscillator performance. (a) Effect on temperature sensitivity; (b) effect on short-term frequency stability. From Ref. 26. (c) Copyright 1981 Hewlett-Packard Company. Reproduced with permission.

JHU/APL began development of an oscillator (type 140) using SC-cut resonators in 1980. One of those oscillators achieved an Allan variance of 8.5 X 10^{-14} at 10 and 100 s in 1981, the first time our oscillators consistently demonstrated a stability of <1 X 10^{-13}. Ultra-precise oscillators using SC-cut resonators began to routinely achieve Allan variance below 1 X 10^{-13} [27].

Beginning in 1983, Charles Wenzel started development of low-phase noise oscillators using SC-cut resonators. These early oscillators did not match the noise floor of the Charles Stone oscillators. However, the Wenzel oscillator used a different design approach that produced a relatively small, low-power oscillator. In 1989 a new series of oscillators named Ultra-low Noise oscillators was introduced. These oscillators had a £*(f)* of -120 dBc 1 Hz from the carrier and a noise floor of -178 dBc. Because the SC-cut resonator is less sensitive to high drive level, the aging rate of these oscillators is approximately 1 X 10^{-10}/24 hours [28, 29]. The phase noise performance of this oscillator is shown in Fig. 2.

The BVA Resonator—A New Class

Another important development in resonator technology occurred in 1976. A new class of resonator, the BVA, was introduced by Raymond Besson [30]. The BVA resonator has two distinguishing characteristics: (1) the electrodes are not deposited on the active vibrating area of the resonator, and (2) the vibrating frequency determining part of the resonator, the connecting structures between the resonator, and the passive mounting ring are machined from a single quartz disk. Electrodes are deposited on the quartz condenser disks that are made from adjacent slices of quartz from the same bar. These condenser plates are located on each side of the vibrating resonator disk, forming a three-piece sandwich. The BVA resonator has the following advantages: this resonator configuration is very rugged and has high immunity to shock and vibration, it is less sensitive to ionizing radiation, it is less sensitive to acceleration, and it has an improved aging rate. Using an AT-cut BVA resonator in a very complicated oscillator setup, NBS demonstrated a frequency stability of 8 X 10^{-14} in 1978 [31]. This was the first published data of stability less than 1 X 10^{-13} we found.

The first commercial oscillator to use a BVA resonator was the Oscilloquartz model 8601, introduced in 1980-1981 [32]. The resonator was an AT-cut, 5-MHz, 5th overtone device. This oscillator had an Allan variance of 3.5 X 10^{-13} at 10 s and an aging rate of » 5 X 10^{-12}/24 hours. The 8601 began using a 5-MHz. 3rd overtone, SC-cut resonator in the late 1980s, which improved their performance. Phase noise £*(f)* was reduced to – 137 dBc 1 Hz from the carrier, and the Allan variance was reduced to 1 to 2 X 10^{-13}. The aging rate remaining in the low 10^{-12} area. The SC-cut 8601 was the best commercial oscillator available at the time, when its combined performance of low phase noise, good Allan variance, and low aging rate is considered. Some of the 8601 oscillators and the spacecraft oscillators described below exhibited frequency jumps [33, 34] that were troublesome in some applications.

A New Generation of Spacecraft Oscillators

JHU/APL initiated development of an oscillator (type 142) to be used on the TOPEX/POSEIDON spacecraft in 1988, using 5-MHz, 3rd overtone, SC-cut BVA resonators made by Oscilloquartz. Several oscillators using this design were made for the TOPEX/POSEIDON [33] and for ground-based reference oscillators. One of these oscillators had an Allan variance of 3.7 X 10^{-14} at 10 s and £*(f)* of – 137 dBc 1 Hz from the carrier as shown in Fig. 2. This is the best reported performance that has been published [35]. Additional performance data for these oscillators are shown in Table 2. The TOPEX/POSEIDON spacecraft was launched in 1991.

The new Frequency Electronics spacecraft oscillator model EF2138 was used in several spacecraft in 1992 [36]. Frequency and Time Systems also had a new spacecraft oscillator in 1993, the model 9500 [37]. Performance data for these oscillators are presented in Table 2. These oscillators have improved frequency stability and phase noise performance and reduced temperature coefficients compared to the oscillators in the 1974 era, as shown in Table 2.

The term ultra-precise oscillator is not well defined, and the definition has certainly changed over time. The oscillators we launched in the early 1960s that had frequency stability of 1 X 10^{-9} were just as difficult to build then as oscillators with frequency stability of 1 to 2 X 10^{-13} are today. There have certainly been over 1500 ultra-precise oscillators placed in orbit and, if the definition is opened up to include oscillators that have some form of active temperature control, the number probably exceeds 3000.

The reliability of spacecraft ultra-precise quartz oscillators is phenomenal. Without clearly defining what constitutes a failure, the number of quartz oscillator failures in orbit is between 1 and 3, a maximum failure rate of 0.002. One oscillator operated continuously for over 21 years and was still fully operational when the spacecraft was turned off [38].

Any discussion of ultra-precise quartz oscillators in a space environment without considering ionizing radiation would be negligent. The energetic charged particles in space, especially protons, will cause the output frequency of the oscillator to change. This problem was recognized early in the space program. The first radiation paper we found in the Frequency Control Symposium Proceedings was published in 1960 [39]. The magnitude of the frequency change is dependent on many factors: the orbit of spacecraft, how well the reasonator is processed during manufacturing [40, 41]. Resonators are sensitive to both radiation dose and dose rate. The reasonator's response to a high radiation dose (krad) is quite different from its response to a low dose (1 to 5 rad) and very nonlinear. Resonators have wide variations in sensitivity to low-level radiation, 1 X 10^{-9} to <1 X 10^{-11}. By starting with good raw quartz and processing the resonators with care, radiation sensitivities of 3 to 5 X 10^{-11}/rad can be achieved.

Radiation sensitivity and acceleration sensitivity of quartz resonators are the largest environmentally induced frequency change in spacecraft oscillators today.

The Tactical BVA Resonator

A second-generation BVA resonator, the tactical BV A, was developed in 1989 [42]. This resonator operates at 10 MHz and is enclosed in an HC-40 holder. The tactical BVA is a smaller, more rugged resonator that is not mechanical resonant below 2000 Hz and will survive relatively high levels of vibration. JHU/APL has been developing a small, low-mass oscillator (type 150) using the tactical BVA resonator without a shock isolation system [43]. The frequency stability and phase noise close to the carrier of this oscillator are very good, but the oscillator does not match the performance of a 5-MHz oscillator because the *Q* of the tactical BVA is only 1.3 X 10^6 compared to a *Q* of 2.5 X 10^6 of a 5-MHz resonator. See Table 2 for additional data on this oscillator.

Historical Performance

The historical performance of ultra-precise quartz oscillators is presented in Fig. 4. The aging rate for spacecraft oscillators has improved by approximately 10,000, whereas there has been very little improvement in ground-based oscillators. Some 2.5-MHz oscillators had superb aging rates in the 1960s that is not often matched by today' s oscillators. The improvement in short-term frequency stability as a function of time is not as easy to compare. In the 1960s short-term stability was calculated using RMS routines and, later, by the Allan variance method. The two are not directly comparable. However, if this fact is ignored, short-term stability has improved by a factor of 100 to 1000. Table 1 presents data from two oscillators with the best Allan variance of their era.

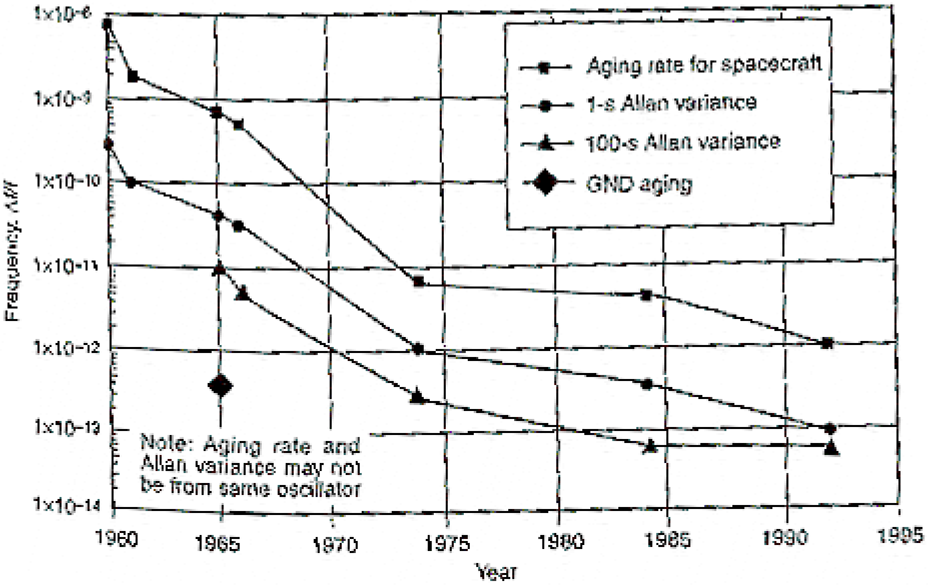

Figure 4. Historical frequency stability of quartz oscillators.

Conclusions

Ultra-precise oscillator performance has improved in almost all categories in the last 40 years. While daily aging rates have not improved very much in absolute terms, the percentage of oscillators that have very good aging rates is much higher today. The improvements made in short-term frequency stability are dramatic. Oscillator phase noise and phase noise measurement systems, which were not even considered at the beginning of this era, have also been dramatically improved. Environmental effects on frequency have been reduced almost to the oscillator noise level except for ionizing radiation and acceleration. Size, mass, and power have been reduced to a fraction of their values in the late 1950s. Vastly improved quartz resonator technology is responsible for a large percentage of the advances of oscillator performance. Oscillator circuitry, packaging techniques, and new semiconductors have also significantly contributed to improved oscillator performance.

Authors' Comments

One disturbing trend appears to be developing that may curtail the future improvements in quartz oscillator technology and may possibly even threaten current oscillator performance levels. Interest in producing quartz resonators with the very best frequency stability is decreasing in the United States. Perhaps this is economically driven because the quantity of the very highest precision resonators is relatively small. But there are some applications that still require a frequency stability (Allan variance) of 5×10^{-14} or better at 10 to 1000 s. Meeting these requirements today is becoming exceedingly difficult, even more difficult than they were two or three years ago. If the requirements for 5×10^{-14} (Allan variance) oscillators are real and the frequency control community is serious about meeting this requirement, resources should be devoted to reversing the backward trend in high-quality resonators.

Acknowledgments

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Table 2. Chronological comparison of oscillators.

	Manufacturer							
						Freq &		
	Western Electric	JK/Sulzer	JHU/APL	Sulzer	Sulzer	Time Sys	Freq Elec	JHU/APL
Model	GS-60158	FS-1100T	110	2.5A	1170	1251	2098A	TIP
Output frequency,								
MHz	2.5	1	3	2.5	5	5	5	5
Aging rate/24 hours	3.30 X 10^{-11}	5.00 X 10^{-10}	8.00 X 10^{-9}	<5 X 10^{-13}	5.00 X 10^{-10}	<1 X 10^{-10}	2.70 X 10^{-11}	6.00 X 10^{-12}
Short-term stability, s								
1		2.2 X 10^{-11} RMS	6.2 X 10^{-11} RMS	5.70 X 10^{-12}		1.00 X 10^{-12}	3.00 X 10^{-12}	4.78 X 10^{-12}
10				6.10 X 10^{-13}		5.00 X 10^{-13}	2.00 X 10^{-12}	3.16 X 10^{-13}
100		±3 X 10^{-11} p-p		2.90 X 10^{-13}		1.00 X 10^{-12}	1.50 X 10^{-12}	2.75 X 10^{-13}
Phase noise freq. offset, Hz								
1					- 110	- 123		
10					- 147	- 142	- 122	- 129

100						- 158	- 144	- 132	- 129
1000						- 159	- 144	- 160	- 133
10000						- 160	- 144	- 169	- 135
Temp. coeff./° C		<1 X 10^{-9}	±2 X 10^{-11}		<7.20 X 10^{-12}		5.00 X 10^{-12}	1.60 X 10^{-12}	1.37 X 10^{-12}
Input power, W		50	2	0.11	2.9		2	2.3	0.6
Mass, 1b		50	7	8	3.5		1.9	2.6	1.1
Volume, in^3		4588.5	315	47.3	283.5	16	62.1	58.57	57.6
Year		1957	1958	1960	1962	1969	1973	1974	1974

Table 2. Chronological comparison of oscillators. (continued)

	Manufacturer								
	Austron	HP	Oscilloquartz	JHU/APL	Wenzel	Freq Elec	JHU/APL	FTS	JHU/APL
Model	1120S	10811 A/B	8601	Type 140		EF-2138	Type 142	9500	Type 150
Output frequency,									
MHz	5	10	5	5	5	5	5	4	10

Aging rate/24 hours		5.00 X 10^{9}	5.00 X 10^{-10}	3.00 X 10^{-11}	4.00 X 10^{-12}	<1.00 X 10^{-10}	3.00 X 10^{-11}	8.10 X 10^{-11}	5.00 X 10^{-11}	2.6 X 10^{-12}
Short-term stability, s										
1		8.00 X 10^{-12}	2.40 X 10^{-12}	1.60 X 10^{-13}	3.50 X 10^{-13}		2.00 X 10^{-12}	8.38 X 10^{-14}	8.00 X 10^{-13}	2.70 X 10^{-13}
10		1.10 X 10^{-11}	1.30 X 10^{-12}	1.70 X 10^{-13}	8.90 X 10^{-14}		5.00 X 10^{-13}	3.74 X 10^{-14}	2.00 X 10^{-13}	1.60 X 10^{-13}
100			3.00 X 10^{-12}	1.90 X 10^{-13}	6.60 X 10^{-14}		5.00 X 10^{-13}	6.09 X 10^{-14}	4.00 X 10^{-13}	1.50 X 10^{-13}
Phase noise freq. offset, Hz										
1		- 110	- 90	- 137	- 121	- 120	- 130	- 137	- 125	- 110
10		- 150	- 120	- 152	- 139	- 150	- 145	- 149	- 143	- 140
100		- 174	- 140	- 154	- 147	- 170	- 151	- 155	- 153	- 152
1000		- 180	- 157	- 155	- 150	- 176	- 151	- 157	- 163	- 158
10000		- 181	- 160	- 155	- 150	- 178		- 156	- 165	- 158
Temp. coeff.° C			5.00 X 10^{-12}	3.70 X 10^{-12}	8.60 X 10^{-13}	2.00 X 10^{-11}	2.00 X 10^{-12}	4.30 X 10^{-13}	3.00 X 10^{-12}	8.00 X 10^{-14}
Input power, W		4.8	2	4.5	0.9	2.5	2.2	1.48	4	0.34
Mass, 1b		0.75	0.7	1.87	1.7		1.75	4.2	6	0.44

Volume, in^3	21.26	13.71	48.97	44	5.14	33.75	106	221.88	8.66
Year	1975	1979	1980	1984	1990	1992	1993	1993	1996