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DEPARTMENT OF DEFENSE
ADVISORY GROUP ON ELECTRON DEVICES
WORKING GROUP A (MICROWAVE DEVICES)

SPECIAL TECHNOLOGY AREA REVIEW ON FREQUENCY CONTROL DEVICES

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DEPARTMENT OF DEFENSE

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Foreword

Frequency Control Device Technology is of vital importance to the DoD since the accuracy and stability of frequency sources and clocks are key determinants of the performance of radar, C^3I, navigation, surveillance, EW, missile guidance, and IFF systems.

The Advisory Group on Electron Devices (AGED) has determined that both additional research and development and, most importantly, the implementation and sustenance of capabilities for manufacturing of the needed frequency control components, rapidly and at an affordable cost, are urgently required.

The payoff from these activities will be the ability to field systems such as GPS, MILSTAR, Joint STARS, Patriot, AMRAAM, JTIDS and many others with greatly improved performance characteristics including increased accuracy and range. In addition, system reliability will be enhanced and costs minimized.

However, present funding for frequency control devices is grossly inadequate. DoD requirements, both present and future, will go unmet as a consequence of that funding shortfall. The group therefore recommends that funding for frequency control devices be increased.

This report documents the findings from the review and assessment of the frequency control device technology area that culminated in the above recommendations. Working Group A of AGED began the review and assessment of this important technology area with a Special Technology Area Review (STAR) held on 21-22 March 1995 at Palisades Institute for Research Services, Inc., Arlington, VA. Working Group A members are subject matter experts in microwave material, device and circuit technology. The group includes representatives from the Army, Navy and Air Force as well as consultants from industry and academia. Its primary responsibility is to advise the DoD on matters relating to microwave and millimeter wave device research and development. STARs are conducted aperiodically by the AGED and its Working Groups to assess specific questions about technologies of importance to the DoD. The examination of frequency control devices was initiated following reports of significant deficiencies for support of DoD system upgrades.

On behalf of WG-A, I would like to take this opportunity to express my sincere appreciation to all of the people who took part in this study—listed on the next page—for their valuable contributions. This applies particularly to Pete Rodrigue of Georgia Institute of Technology who organized and chaired this review and to Dr. Susan Turnbach, OUSDA&T, whose support and encouragement were essential for the successful completion of this effort. John Vig of the Army Research Laboratory is also thanked and commended for significant contributions to this study. His expertise and excellent background material helped immensely in the preparation of this report.

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EXECUTIVE SUMMARY

Frequency Control Device Technology is of vital importance to the DoD since the accuracy and stability of frequency sources and clocks are key determinants of the performance of radar, C^3I, navigation, surveillance, EW, missile guidance, and IFF systems.

The Advisory Group on Electron Devices (AGED) has determined that both additional research and development and, most importantly, the implementation and sustenance of capabilities for manufacturing the needed frequency control components, at an affordable cost, are urgently required.

The payoff from these activities will be the ability to field systems such as GPS, MILSTAR, Joint STARS, Patriot, AMRAAM, JTIDS and many others with greatly improved performance characteristics including increased accuracy and range. In addition, system reliability will be enhanced and costs minimized.

SPECIFIC FINDINGS:

1. High performance frequency control devices are vital components of a large number of high priority DoD systems. They represent an enabling technology upon which the satisfactory performance of systems such as GPS, MILSTAR, Joint-STARS, AMRAAM, and many classified programs are dependent.

2. Unmet, DoD-unique requirements exist:

    - high-accuracy low-power clocks
    - low-noise vibration-resistant oscillators
    - gun-hardened oscillators/clocks
    - radiation-hardened oscillators
    - man portable, real time, chemical and biological sensors

3. An adequate manufacturing infrastructure must be put into place to assure the availability of required frequency control components, at an affordable cost, as needed for DoD system use. The R&D and industrial bases have eroded drastically—to the point where systems have begun to encounter difficulties obtaining the required frequency control devices. This trend is likely to accelerate as companies who previously specialized in DoD business shift their focus to commercial markets.

4. R&D opportunities which promise significant military advantages in the future are not being adequately explored. These include:

    - new piezoelectric materials
    - ultrahigh stability acoustic resonators
    - resonator theory
    - modeling and computer aided design of resonators and oscillators
    - new processing and packaging methods
    - low-power high-accuracy clocks
    - smart clocks
    - miniature and high-performance atomic clocks
    - microresonators and thin-film resonators and their applications as chemical, biological and room-temperature infrared sensors

5. Concurrently, with the execution of research and development activities, **planning for the transition of successful results to affordable manufacturing must be accomplished** and the plan implemented.

6. DoD laboratory funding has been grossly inadequate, which has resulted in most DoD R&D being performed with specific program funds, aimed at solving a narrow range of acquisition driven problems. This has led to limitations on the spread of technology advances to only a small fraction of the DoD systems that could benefit from them.

7. The low level of DoD funding does not provide adequate support for sustaining the training and research infrastructure at universities.

SPECIFIC RECOMMENDATIONS:

Recommendation: **DoD should increase the funding of this technology area to a level that will be sufficient to revitalize and sustain a DoD specific technology base, ensure availability of industry vendors to service DoD needs, and stimulate new university and industry R&D activity.**

The funding should be used to:

1. Sponsor long-term R&D programs at a few organizations to allow these organizations to maintain a core R&D capability that is sufficient for meeting future DoD-unique needs.

2. Develop and implement a viable plan to transition successful R&D results to manufacturing. Provide funding support to assure that the appropriate manufacturing infrastructure capable of meeting DoD frequency control component needs is put into place **and sustained**. Identify and eliminate production deficiencies.

3. Perform selected demonstration projects that illustrate the value of funded efforts to DoD systems.

4. Restore and maintain a DoD in-house core competence for frequency control technologies of military importance. In-house responsibilities will include the following activities: a) a coordinated effort aimed at satisfying DoD-unique requirements, b) identifying and capitalizing upon militarily significant R&D opportunities, and c) assisting with the resolution of frequency control technology issues for both fielded and developmental systems. As appropriate, joint programs will be formed with non-DoD government laboratories, for example, in the area of small atomic clock development.

5. Establish frequency control centers of excellence at two competitively selected universities—one to specialize in piezoelectric frequency control technology and one to specialize in atomic clock technology. Institute and maintain long term programs to foster innovation, solve DoD relevant technology problems, and train future workers. Establish small, innovative research efforts at several other universities.

Specific research and development programs recommended for implementation are:

- high perfection quartz development
- new piezoelectric materials—growth and characterization
- theory, modeling and computer aided design of resonators and oscillators
- processing and packaging technologies
- microresonators, thin film and other microwave resonators
- low power, high accuracy quartz clocks
- low noise resonators and oscillators
- smart clocks
- miniature, and high performance optically pumped atomic clocks
- resonator based chemical, biological and uncooled IR sensors

This revitalization program should be closely coordinated among the organizations receiving funding for both technology developments and applications. The coordination effort, administered by a designated government laboratory, should be facilitated through quarterly meetings that are attended by representatives of all participating organizations. These meetings should include progress reviews, discussion of critical problems and planning of future directions.

Report on Special Technology Area Review on Frequency Control Devices

INTRODUCTION:

Frequency control devices and clocks play critically important roles in military radar, communication, navigation, surveillance, missile guidance, EW, and IFF systems. DoD requirements and DoD laboratories have historically driven high performance frequency control technology. Many of the requirements continue to be DoD-unique. Because the frequency control industry and DoD support of this technology have both declined significantly in recent years, there is growing concern that the frequency control devices needed by the DoD may not be available in the future. Working Group A of the DoD Advisory Group on Electron Devices (AGED) held a Special Technology Area Review (STAR) in March 1995, to determine whether or not DoD investment is adequate in this technology area. This report details the STAR's findings, and the AGED Working Group A's recommendations.

DOD RESPONSIBILITY AND CURRENT STATUS OF FREQUENCY CONTROL DEVICE TECHNOLOGY:

Upon the creation of Joint Directors of Laboratories (JDL) Reliance, the Army was assigned the role of lead Service[1] for frequency control and, in accordance with Reliance policy, the AF and Navy eliminated their R&D programs in this technology.

The U.S. industrial base for frequency control devices, measured by both its absolute size and by share of the worldwide market, has declined drastically in the last 10 years. While the world market has more than doubled, domestic manufacturers' output has declined more than two-fold. The low and medium precision, high-volume business has moved to Asia (e.g., oscillators for watches, PCs, cars, pagers, cellular telephones, etc.). The high-end, low-volume business is primarily for DoD and NASA, but this market represents less than 4% of the total market. Industrial R&D, and the industrial talent base, have also declined drastically in the USA. University research is minimal. About three or four companies are left to respond to high-end DoD needs. US researchers have been producing a declining percentage of the world's total research literature in this technology.

WHY IS IT IMPORTANT FOR DOD TO SUPPORT RESEARCH AND DEVELOPMENT OF FREQUENCY CONTROL DEVICES?

Nearly all electronic products contain frequency control devices. Major commercial applications include watches and clocks, communication devices, computers, automobiles, and home entertainment systems. Frequency control devices are used as frequency sources, clocks, filters,

[1] A lead Service has the primary responsibility for research and development activities in a designated technology area.

and sensors. Worldwide production is in excess of 2 billion devices per year. However, over 99% of this production is of devices for commercial applications.

DoD systems such as GPS, MILSTAR, Joint STARS, Patriot, AMRAAM, JTIDS, EW systems, and many classified programs require clocks with much higher accuracy and oscillators with much lower noise than those required for commercial applications. Future improvements in the performance of DoD weapon systems are contingent upon the availability of frequency control devices with accuracy, performance and reliability characteristics that far exceed those currently available.

Frequency control device performance has a marked effect on overall system performance. For example:

- Many systems utilize spread spectrum techniques for **jamming resistance and for hiding signals**. With clocks of sufficiently high accuracy, it is possible to make frequency hopping systems virtually invulnerable to smart jammers. This occurs if the transmitter-to-jammer-to-receiver propagation delay (3.3 μs/km) exceeds the dwell time per hop, i.e., if the radio hops to the next frequency before the jamming signal at the previous frequency can reach it. At present, the only way that such fast hopping can take place is with the use of atomic clocks. These are expensive and available only in small quantities. However, with further development, low power quartz clocks may also provide the required accuracies.

- Precise time is essential for precise **navigation**. Modern navigation systems utilize ultraprecise clocks and radio transmissions of precisely timed navigation signals. The Global Positioning System (GPS) is the most accurate worldwide navigation system available today. In GPS, navigation is accomplished by one-way time measurements. Atomic clocks in the satellites and quartz oscillators in the receivers provide the required nanosecond-level accuracies. Receiver oscillator noise affects both the navigation accuracy and the jamming margin; the medium-term (10 to 1000 second) stability affects the reacquisition capability, system integrity monitoring, and performance in a high-jamming environment; the long-term stability affects the time-to-subsequent fix and the capability to operate with fewer than four satellites; the warm-up time of the oscillator affects the time to first fix; the power requirement and the size of the oscillator affect the receiver's battery life, mission duration, and weight.

- Gun-hardened oscillators are required for **smart munitions, air-dropped and artillery emplaced sensors, fuzes, and space defense systems**. Both the Army and the Navy have precision guided munitions (PGM) programs. A critical component of these systems is the gun-hardened oscillator/clock. With a sufficiently accurate and shock-resistant clock, a GPS receiver in a projectile can "acquire" the satellites soon after being fired and help to accurately guide the projectile to its target. Development of highly accurate, affordable PGMs will represent a major advance in defense capabilities. Currently used projectiles are virtually the same as those used in WW II, i.e., they are unguided and are inaccurate, especially at long ranges. With PGM, many fewer projectiles will be needed to destroy a target. Thus, the overall cost of projectiles is reduced as well as associated logistics and collateral damage costs.

- Low noise oscillators are essential for modern **surveillance systems,** particularly Doppler radars. The velocity of the target and the radar frequency are primary determinants of the phase noise requirements. Slow-moving targets produce small Doppler shifts, therefore, low phase-noise close to the carrier is required. To detect fast-moving targets, low noise far from the carrier is required.

- **Missile guidance systems** benefit greatly from improvements in vibration-resistant low-noise oscillators. When a missile is guided by ground radar, the radar is vulnerable to anti-radiation missiles and other countermeasures. Placing the radar on-board the missile can greatly reduce the vulnerability, but at the expense of placing much greater demands on missile components, especially the reference oscillator. High vibration levels degrade the oscillator phase noise by a wide margin. Vibration-insensitive low-noise oscillators are required for on-board radar systems.

- Friendly-fire casualties due to lack of adequate **identification-friend-or-foe (IFF) systems** have been a major problem in recent wars. Precise timing can play a major role in solving this problem. For example, cooperative IFF systems use an interrogation/response method which employs cryptographically encoded spread spectrum signals. The interrogation signal received by a friend is supposed to result in the "correct" code being automatically sent back via a transponder on the friendly platform. The "correct" code must change frequently to prevent a foe from recording and transmitting that code ("repeat jamming"), thereby appearing to be a friend. The code is changed at the end of what is called the code validity interval, CVI. The better the clock accuracy, the shorter the CVI can be, the more resistant the system can be to repeat jamming, and the longer can be the autonomy period for users who cannot resynchronize their clocks during a mission. The CVI chosen is usually dictated by the accuracies achievable with low-power oscillators. For example, the (now canceled) Mark XV system's CVI was dictated by the accuracies achievable with low-power clocks rather than the much shorter CVI desired by the NSA.

- **Electronic warfare**, e.g., the ability to locate radio emitters is important. One method of locating emitters is to measure the time difference of arrival of the same signal at widely separated locations. Emitter location by means of this method depends on the availability of highly accurate clocks, and on highly accurate methods of synchronizing clocks that are widely separated. Since electromagnetic waves travel at the speed of light, 30 cm per nanosecond, the clocks of emitter locating systems must be kept synchronized to within nanoseconds in order to locate emitters with a high accuracy. Without resynchronization, even the best available militarized atomic clocks can maintain such accuracies for periods of only a few hours.

  An important electronic warfare application for frequency sources is the **ELINT** (ELectronic INTelligence) receiver. These receivers are used to search a broad range of frequencies for signals that may be emitted by a potential adversary. The frequency source must be as noise-free as possible so as not to obscure weak incoming signals. The frequency source must also be extremely stable and accurate in order to allow accurate measurement of the incoming signal's characteristics.

- **Radar spoofing** is another important application. By replicating phase coherence patterns, it is possible to spoof coherent radar systems, however, this requires very low noise oscillators.

- In **digital communication systems**, synchronization plays a critical role because it ensures that information transfer is performed with minimal buffer overflow or underflow events, i.e., with an acceptable level of "slips." Slips cause problems, e.g., missing lines in FAX transmission, clicks in voice transmission, loss of encryption key in secure voice transmission, and data retransmission. High data rate strategic communication systems require 1×10^{-11} or better frequency accuracy, which can be obtained currently only from (large and expensive) cesium beam standards.

WHAT PERFORMANCE CHARACTERISTICS ARE OF PARTICULAR IMPORTANCE FOR MILITARY APPLICATIONS?

- The ability to **deny systems to unauthorized users** is greatly influenced by the clock. For example, because GPS can be used against us by even technologically unsophisticated adversaries, it is essential that we be able to deny the GPS signal to adversaries in wartime, without also denying it to friendly forces. The GPS satellites emit two codes: the C/A code, which provides ~100 meter accuracy, is easy to spoof and jam, but can be acquired with receivers that use inexpensive clocks; the P/Y-code, which provides 10x higher accuracy than the C/A code, is more difficult to jam, is very difficult to spoof, is accessible to DoD users only, but acquiring it directly (i.e., without first acquiring the C/A code) requires a high accuracy clock in the receivers. In wartime, we can deny GPS to adversaries by jamming the C/A code, but this requires receivers which can acquire the P/Y-code directly. Such acquisition requires about a 100 microsecond clock accuracy, which can be maintained with currently available low-power clocks for only short periods (seconds to minutes). Atomic clocks can maintain that accuracy for much longer periods, however, atomic clocks are not suitable for small receivers as they require too much power, and are too large, heavy, and expensive. Low power clocks need to be developed which can maintain the 100μs accuracy for extended periods.

- The **autonomy period (radio silence interval)** and the **signal acquisition (net entry) time,** i.e., the speed with which a communication link can be established, depends on the speed with which a transmitter's signal can be acquired by the receiver. This is strongly dependent on the frequency difference between transmitter and receiver. In spread spectrum systems, it is also dependent on the time difference between the transmitter's clock and the receiver's clock. The larger these differences, the longer it takes to search and acquire. While searching, the system is more vulnerable to interception, jamming and spoofing than at other times. For acquiring weak signals, the noise of the receiver's reference oscillator can also affect the acquisition. In GPS, for example, to acquire the P/Y code directly and rapidly, the oscillator/clock must possess good frequency and time accuracies (atomic clocks can provide such accuracies, but the low-power clocks in hand-held receivers cannot). The acquisition time increases rapidly with increasing frequency and time errors because the receiver must perform a twodimensional search—in both frequency and time space. The time to directly acquire the P/Y code can take years if an inexpensive clock is used in the receiver!

- The **power required by oscillators** has an important effect on system performance and operating costs. When the system is not being used, everything except the clock can usually be turned off. As a result, the power requirement of the clock is a major determinant of battery consumption. For example, to power the time and frequency unit in a MILSTAR satellite terminal (SCOTT) during the required 10 day standby period, a battery pack weighing 18 kg was initially required. By replacing the power-hungry oven-controlled crystal oscillator of the original design with an experimental device, the microcomputer compensated crystal oscillator (MCXO), which is a much lower power oscillator of similar accuracy, 12 kg of battery weight could be saved.

  Another reason for minimizing the power dissipation of oscillators is that the dissipation produces undesirable infrared signatures which makes the system easier to detect by an adversary. The cost savings resulting from reducing the power requirements of oscillators can be large. During a conflict, radios making use of these oscillators would, of course, be used 24 hours per day, for an even greater saving; however, the real benefit of lower power radios is a lighter, more mobile force, which can operate for longer periods without needing battery replenishment. For example, for SINCGARS, the cost savings resulting from reducing the power requirement for the radios' 20 year life, (assuming peace-time usage of 2 hours per day) has been estimated to be more than $1 million per mW of power saving!

- Most air defense systems cannot cope with stealth aircraft. **To detect stealthy targets, the radar systems must compensate for the smaller reflections by significantly increasing the transmitted power**, which is often not feasible, or by significantly improving the radar receiver's sensitivity. Higher sensitivity results in receiving more clutter and false targets. In addition, very low noise reference oscillators are required for detecting targets under such conditions.

- Historically, the subject of frequency control is intimately related to the subject of **frequency spectrum utilization**. In both commercial and military systems, to allow for more users in a given frequency band, it was necessary to reduce the channel spacings, which required the tightening of the frequency tolerances allowed in both the transmitters and receivers. As the number of users grew, and as technology allowed the allocation of higher frequency bands, the frequency tolerances became tighter and tighter. The frequency accuracy requirements of tactical radios prior to the advent of spread spectrum techniques were typically 10 to 50 ppm. Radios that employ spread spectrum techniques today require 5 ppm to 0.0001 ppm oscillators. The noise of oscillators can also limit the capacity of communication systems. Since the noise from a transmitter in one channel extends to neighboring channels, as the number of transmitters grows, the noise accumulates to the point where receivers can no longer function properly. For example, in one L-band satellite communication system, the vibration-induced phase noise is a serious limitation on the number of users per transponder when the users are on vibrating platforms, such as aircraft, trucks, etc. The noise from a typical oscillator (2×10^{-9} per g vibration sensitivity) limits the number of users to less than 100 per transponder, whereas a state-of-the-art oscillator (2 x 10^{-10} per g vibration sensitivity) can allow as many as 1200 users per transponder. Since the rental of a commercial transponder costs >> $1 million per year, the economic impact of oscillator noise can be significant.

- When a radar is on a stationary platform, the **phase noise requirements** can usually be met with commercially available oscillators. A good quartz crystal (BAW) oscillator can provide sufficiently low noise close to the carrier, and a good SAW oscillator can provide sufficiently low noise far from the carrier. The problem with achieving sufficiently low phase noise occurs when the radar platform vibrates, as is the case when the platform is an aircraft or a missile. The vibration applies time-dependent stresses to the resonator in the oscillator which results in modulation of the output frequency. The aircraft's random vibration, thereby, degrades the phase noise, and discrete frequency vibrations (e.g., due to helicopter blade rotation) produce spectral lines which can result in false target indications. The degradation in noise spectrum occurs in all types of oscillators (BAW, SAW, atomic frequency standards, etc.) Figure 1 shows an example of a typical aircraft random vibration envelope (in the upper right hand corner), and the resulting phase noise degradation.

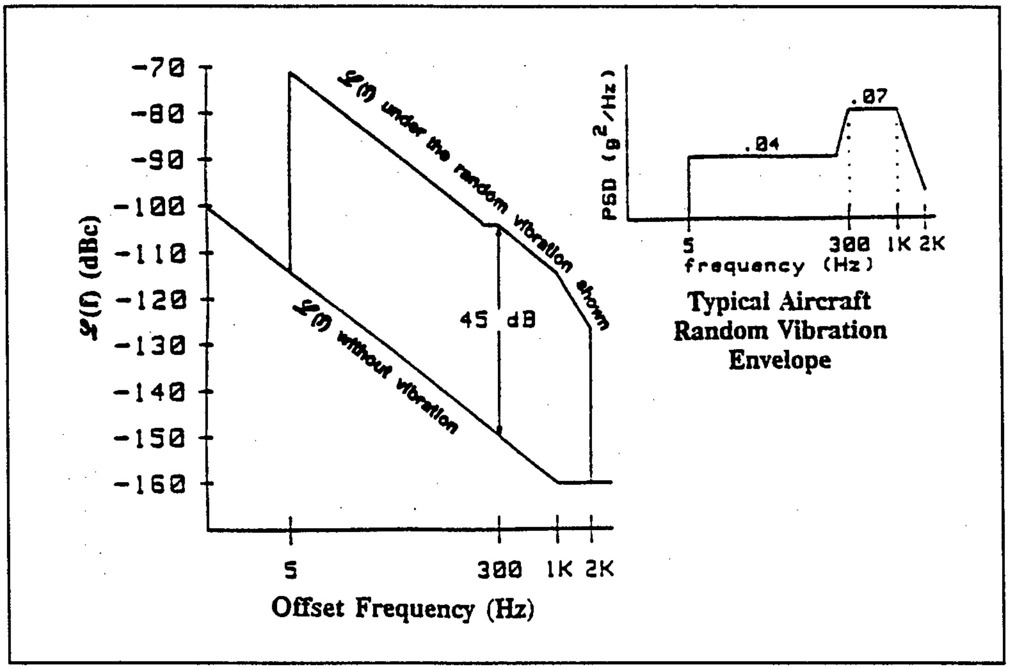

Figure 1 - Random Vibration Envelope and the Resulting Phase Noise Degradation
Oscillator phase noise degradation caused by random vibration of a typical aircraft, whose random vibration envelope is shown in the upper right. The phase noise shown is for a 10 MHz oscillator, with a 1 x 10^{-9} per g acceleration sensitivity.

Such a large degradation can have catastrophic effects on radar performance. In a coherent radar, the platform-vibration-induced phase noise can reduce the probability of detection to zero.

The phase noise of oscillators can lead to erroneous detection of phase transitions, i.e., to bit errors, when phase-shift-keyed (PSK) digital modulation is used. For example, when 8-ary PSK is used, the maximum phase tolerance is ±22.5°, of which ±7.5° is the typical allowable carrier noise contribution. Due to the statistical nature of phase deviations, if the RMS phase deviation is 1.5°, for example, the probability of exceeding the ±7.5° phase deviation is 6×10^{-7}, which can result in a bit error rate that is significant in some applications.

- Conventional (i.e., "monostatic") radar, in which the illuminator and receiver are on the same platform, is vulnerable to a variety of countermeasures. Bistatic radar, in which the illuminator and receiver are widely separated, can greatly reduce the vulnerability to countermeasures such as jamming and antiradiation weapons. The transmitter can remain far from the battle area, in a "sanctuary." The receiver can remain "quiet." The **timing and phase coherence** problems can be orders of magnitude more severe in bistatic than in monostatic radar, especially when the platforms are moving. The two reference oscillators must remain synchronized and syntonized during a mission so that the receiver knows when the transmitter emits each pulse, and so that the phase variations will be small enough to allow a satisfactory image to be formed. Low noise crystal oscillators are required for short term stability; atomic frequency standards are often required for long term stability.

- **Shock and vibration** can produce large phase deviations even in "low noise" oscillators. Moreover, when the frequency of an oscillator is multiplied by N, the phase deviations are also multiplied by N. For example, a phase deviation of 10^{-3} radian at 10 MHz becomes 1 radian at 10 GHz. Such large phase excursions can be catastrophic to the performance of systems, e.g., those which rely on phase locked loops (PLL) or phase shift keying. Low-noise, acceleration-insensitive oscillators are essential in such applications.

- The **long-term stability and the lifetime of oscillators** have a significant impact on logistics costs. As the oscillator's frequency ages (and all but cesium beam frequency standards do age), or, as e.g., a cesium beam frequency standard nears end of life, at some point, the oscillators must be recalibrated or replaced. A need for frequent recalibration or replacement has a significant adverse impact on the life cycle cost of equipment. Lower aging oscillators do cost more initially; however, the increased cost is often recovered rapidly through a decrease in logistics costs. An important goal of research aimed at reducing oscillator aging is to provide systems that do not require recalibration over the course of their operating life.

- **Radiation hardened oscillators** are required for both ground and space systems. The MILSTAR satellites could have used a quartz oscillator frequency source except for the radiation induced frequency shifts. Instead, the MILSTAR program has spent well in excess of $10M to develop a space qualified rubidium standard.

WHAT ARE THE UNMET, DOD UNIQUE REQUIREMENTS?

Unmet, DoD-unique requirements exist especially in the areas of:

- **gun-hardened oscillators for competent munitions** – a high-accuracy (100 μs) clock which can operate immediately after gun-firing (i.e., after a >16,000 g, 12 ms duration shock) is needed.

- **low-noise vibration resistant oscillators for radar (Joint-STARS), EW (ATRJ), missile guidance (Patriot PAC III upgrade), and radar jamming systems** – a 1000x improvement in the state-of-the-art is needed.

- **low-power high-accuracy clocks for jamming resistant C^3I (MILSTAR terminals), navigation (GPS), and EW (time-difference-of-arrival) systems** – quartz clocks with < 10^{-8} frequency uncertainty (fractional frequency differences) and small atomic clocks with < 10^{-10} frequency uncertainty (fractional frequency differences) are needed.

- **radiation hardened space oscillators (MILSTAR)**;

- **chemical and biological sensors which are man-portable and real-time;** and

- **uncooled IR imaging arrays; and accelerometers** for strategic guidance systems (with dynamic range of 10^9, 0.1μ to 100g range).

Experience has shown that DoD-unique products of today are often the commercial products of tomorrow and enable new commercial applications. For example, temperature compensated oscillators, TCXOs, were developed under Army contracts and under Army in-house programs during the 1960s and 1970s. Today, tens of millions of TCXOs are produced annually for commercial markets, such as cellular telephones. Similarly, atomic clocks were originally developed primarily for DoD and scientific applications, but today, thousands of rubidium standards are used in commercial applications such cellular telephone base stations.

WHAT ARE THE R&D OPPORTUNITIES THAT HAVE POTENTIAL FOR MEETING THESE NEEDS?

Numerous R&D opportunities exist which have the potential for meeting future DoD needs for frequency control devices, and, by so doing, providing the U.S. with a significant military advantage. At present, none of these are being adequately explored because of a lack of sufficient resources. These opportunities include development of:

1. **High perfection quartz** – evidence has been accumulating which indicates that the stability of quartz devices is limited by quartz imperfections, such as dislocations and impurities. The feasibility of growing dislocation free ultrahigh purity quartz has been demonstrated (in the UK), however, there is no commercial demand for such quartz, and DoD demand is too small for suppliers to invest in developing a capability for producing such quartz. **POTENTIAL PAYOFF: Ability to produce and field low power, low cost quartz clocks that make frequency hopping systems virtually invulnerable to smart jammers and improve the ability to locate radio emitters.**

2. **New piezoelectric materials** – quartz has been used exclusively in high stability oscillators because of its unique set of properties. Although quartz is a superb material, it has some serious limitations, such as a phase transition at 573° C which prevents the use of high temperature processes (for purification and stress relief) which would be highly desirable. During the past decade, new piezoelectric materials have been invented which show great promise for providing the advantages of quartz without its limitations, and with potentially higher Q. ("Langasite," a lanthanum gallium silicate, invented in Russia, and lithium tetraborate, invented in the UK, are examples.) Programs to further develop, characterize (e.g., determine their linear and nonlinear material constants as functions of angles of cut and temperature), and establish U.S. sources for these and other (e.g., gallium phosphate) materials are needed. **POTENTIAL PAYOFF: Lower cost, high performance systems.**

3. **Resonator theory, modeling, and computer aided design of resonators and oscillators** – the theory of resonators is highly complex. Until recently, resonator and oscillator design has been an art. Finite element model (FEM) calculations of "real," three-dimensional resonators have not been feasible due to the inordinately long supercomputer calculation times required. With improved supercomputers and algorithms, CAD of resonators and oscillators is becoming feasible. Atomistic models are also becoming feasible with the aid of powerful computers. Research programs at universities are needed to make the required CAD models and simulation capabilities a reality. **POTENTIAL PAYOFF: Improved missile accuracy, better surveillance systems, more accurate on-board radar systems for missile guidance, superior IFF systems, ability to effectively conduct radar spoofing.**

4. **Processing and packaging** of high stability resonators – many of the designs and processes used in high stability resonators were invented more than thirty years ago. Promising new designs, processes borrowed from semiconductor microfabrication technology, and innovative packaging methods have been proposed but not implemented for lack of resources. (The packages used for high-stability resonators today are the same as the ones used 30 years ago.) **POTENTIAL PAYOFF: Lower cost, more reliable, more compact packages.**

5. **Microresonators and thin film resonators** – microresonators and thin film resonators promise to provide miniature (e.g., MMIC compatible) and high frequency (above 100 GHz, in principle) resonators, filters and sensors. Both piezoelectric (quartz and other) and nonpiezoelectric (e.g., silicon) devices show great promise. Silicon microresonator arrays, although not temperature stable, show great promise for on-chip integration as (low frequency) filters and sensors. **POTENTIAL PAYOFF: More compact RF front ends.**

6. **Low power, high accuracy quartz clocks** – the feasibility of achieving a 100x stability improvement over competing technologies with the microcomputer compensated crystal oscillator (MCXO) has been shown, however, to achieve such performance reproducibly, and to extend the performance, the frequency vs. temperature hysteresis problem must first be solved. The noise, power and size of the MCXO also need to be reduced. These problems have not been solved due to inadequate resources. **POTENTIAL PAYOFF: Ability to make frequency hopping systems virtually invulnerable to smart jammers and improve the ability to locate radio emitters.**

7. **Low noise resonators and oscillators** – several technologies for low noise oscillators need to be explored. These include: surface transverse wave resonators and dielectric resonator oscillators for ultralow noise floors, and novel BAW and SAW resonators for vibration insensitive oscillators. Fundamental noise studies, e.g., of 1/f noise, in piezoelectric devices are also needed. **POTENTIAL PAYOFF: Improved missile accuracy, better surveillance systems, more accurate on-board radar systems for missile guidance, superior IFF systems, ability to effectively conduct radar spoofing.**

8. **Smart clocks** – currently, TCXOs are the only oscillators which use compensation for an instability. In principle, with appropriate sensors and a microcomputer, it is possible for the oscillator to "learn" and then to compensate for all systematic instabilities, and to make optimal predictions. (HP is using compensation in their latest cesium standard; however, this standard costs >$50,000.) **POTENTIAL PAYOFF: Error-free digital communication systems, implemented at lower cost.**

9. **Miniature, and high-performance optically pumped atomic clocks** – optical pumping techniques promise significant reductions in the size and weight of atomic frequency standards. ARPA is currently funding a high risk program aimed at a miniature cesium cell standard. Other, less risky approaches need to be explored. Optical pumping techniques can also result in large improvements in the stabilities of high-performance (e.g., space) atomic clocks. **POTENTIAL PAYOFF: Smaller, lighter weight frequency standards.**

10. **Resonator based chemical, biological and uncooled IR sensors** – the large environmental and mass sensitivity capabilities, combined with the low noise of quartz resonators can be exploited to provide unparalleled sensors. Single SAW and BAW resonators coated with appropriate absorbers can provide highly sensitive and selective chemical and biological sensors. Arrays of quartz microresonators can, potentially, provide uncooled IR imaging arrays which are limited by background noise only, and chemical/biological sensors which can sense and identify a multiplicity of species. **POTENTIAL PAYOFF: Miniature chemical and biological sensors that provide outstanding performance in a small housing, at low cost.**

APPENDIX A - A FREQUENCY CONTROL DEVICE PRIMER

Nearly all frequency control devices utilize a piezoelectric material. The material used in most applications is quartz (which is single-crystal silicon dioxide). A quartz crystal acts as a stable mechanical resonator, which, by its piezoelectric behavior and high Q, determines the frequency generated in an oscillator circuit. Bulk-acoustic-wave (BAW) resonators are available in the frequency range from about 1 kHz to 300 MHz. Surface-acoustic-wave (SAW) and surface-transverse-wave (STW) devices are available from about 70 MHz to 2.5 GHz.

In the manufacture of quartz resonators, wafers are cut from a single-crystal quartz bar along precisely controlled directions with respect to the crystallographic axes. The properties of the device depend strongly on the angles of cut (the commonly used cuts have two-letter names, such as AT, SC and ST). After shaping to required dimensions, metal electrodes are applied to the quartz wafer, which is mounted in a holder structure. The assembly is then sealed hermetically.

To cover the wide range of frequencies, different cuts vibrating in a variety of modes, are used. Above 1 MHz, the AT-cut is commonly used. For high-precision applications, the SC-cut has important advantages over the AT-cut. AT—and SC-cut crystals can be manufactured for fundamental-mode operation at frequencies up to about 100 MHz. Above 100 MHz, *overtone* crystals, which operate at a selected harmonic mode of vibration, or SAW devices are used. SAW devices usually use ST-cut quartz.

The hierarchy of BAW oscillators, spanning eight orders of magnitude in accuracy, is shown in Table 1 and Fig. 2. In most crystal oscillators, the largest frequency instabilities are the variations of frequency with temperature and with time (i.e., aging). The three categories of crystal oscillators, based on the method of dealing with the frequency vs. temperature (f vs. T) characteristics, are the crystal oscillator (XO), temperature compensated crystal oscillator (TCXO), and oven controlled crystal oscillator (OCXO).

Table 1 - Hierarchy of Oscillators

Oscillator Type	Accuracy*	Typical Applications
Crystal oscillator (XO)	10^{-5} to 10^{-4}	Computer timing
Temperature compensated crystal oscillator (TCXO)	10^{-6}	Frequency control in tactical radios
Microcomputer compensated crystal oscillator (MCXO)	10^{-8} to 10^{-7}	Spread spectrum system clock
Oven controlled crystal oscillator (OCXO)	10^{-8} (with low noise)	Radar frequency source
Small atomic frequency standard (rubidium cell)	10^{-9}	C^3 satellite terminals, bistatic radar
High performance atomic standard (cesium beam)	10^{-12} to 10^{-11}	Strategic C^3, electronic warfare

* Units are frequency uncertainty (i.e., Δf/f). Accuracy includes the effects of the military environment and one year of aging (all oscillators except cesium standards exhibit frequency aging).

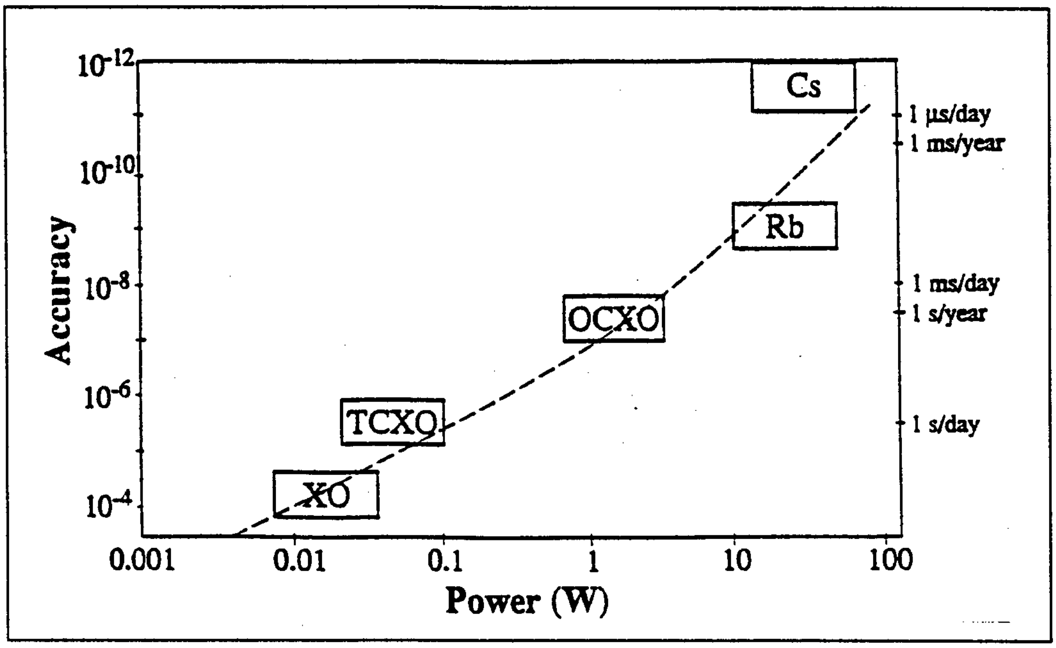

Figure 2 - Accuracy vs. Power Requirements

* Accuracy vs. size (ranging from ~1 cm^3 to 30 liters) and accuracy vs. cost (ranging from < $1 to > $50,000) have a similar relationship. The goal of DoD research is to move the technology towards the upper left corner.

In a simple crystal oscillator, **XO**, the f vs. T characteristic is that of the resonator, i.e., an XO does not contain means for reducing the crystal's f vs. T variations. Typical f vs. T stability over a -40°C to +75°C range is 50 parts per million (ppm). (The stability is dimensionless, as it is a $\Delta f/f$.)

In a **TCXO**, the output signal from a temperature sensor (thermistor) is used to generate a correction voltage that is applied to a voltage-variable reactance (varactor) in the crystal network. The reactance variations compensate for the crystal's f vs. T characteristic. Analog TCXOs can typically provide about 2 to 5 ppm f vs. T stability over a -40°C to +75°C range. The experimental microcomputer compensated crystal oscillator, MCXO, utilizes a high stability SC-cut crystal and digital compensation to achieve a 100X improvement over a TCXO's f vs. T stability.

In an **OCXO**, the crystal and other temperature sensitive components are in a stable oven which is adjusted to the temperature where the crystal's f vs. T characteristic has zero slope. OCXOs can provide a >1000X improvement over the XO's f vs. T variation, but at the cost of requiring a much higher amount of power (typically 1 to 4 watts).

An **atomic frequency standard** produces an output frequency which is determined by the energy difference between two atomic states (per Planck's law, $\Delta E = hf$). A voltage controlled crystal oscillator, VCXO, is locked to the atomic resonance, and the output frequency is that of the VCXO. (Atomic resonators are noisy, so the VCXO is needed for good short-term noise performance.) The three types of atomic standards commonly used today are the cesium beam, rubidium cell, and hydrogen maser standards. The Cs beam standard is the primary standard because the definition of the unit of time, the second, is based on it. About 300 Cs standards are produced annually vs. about 8,000 Rb, and only about 10 H-masers. Typical unit costs are: $50,000 for a Cs standard, $2,500 for a Rb standard, and $200,000 for H-masers. Rb standards exhibit lower performance than Cs standards. H-masers are also less accurate than Cs beam standards; however, they have superior short term stability, which makes them useful in special applications such as radio astronomy.

Piezoelectric crystals are also used as frequency selective components in **filters**. Design techniques can provide band-pass or band-stop filters of prescribed characteristics. Piezoelectric filters can exhibit low insertion loss, high selectivity, and good temperature stability. Filter crystals are usually designed to have only one strong resonance in the region of operation, with all other responses (unwanted modes) attenuated as much as possible. The primary use of **SAW devices** is as filters. SAW filters can provide bandwidths ranging from 0.03% to greater than 10%. Other important SAW device applications are in low-noise UHF oscillators, and in high frequency digital clocks.

A frequency control device's performance is influenced by many factors: noise, aging, temperature, thermal shock, thermal history, static acceleration, vibration, mechanical shock, acoustic noise, ionizing radiation (both photons and particles), magnetic fields, power supply voltage, load impedance, atmospheric pressure and humidity. Designers of high stability oscillators must strive to minimize the effects of these influences over the specified environment and time period.

A significant and emerging application of frequency control devices is in **sensors**. Whereas in frequency control and timing applications of piezoelectric devices the components are designed to be as insensitive to the environment as possible, quartz and other piezoelectric resonators can also be designed to be highly sensitive to parameters such as temperature, pressure, force, acceleration, and mass changes. Quartz-crystal sensors can exhibit unsurpassed resolution and dynamic range. For example, one commercial "quartz pressure gage" exhibits a 1 ppm resolution, i.e., 60 Pa at 76 MPa, and a 0.025% full-scale accuracy. Quartz sorption detectors can detect a change in mass of 10^{-12} g. Quartz accelerometer/force sensors are capable of resolving 10^{-7} to 10^{-8} of full scale. Quartz thermometers can provide sub-microdegree sensitivity and sub-millidegree absolute accuracy over wide temperature ranges; and microresonator arrays promise to provide room temperature IR imaging systems which are limited by background noise only.

APPENDIX B - EXAMPLES OF SYSTEM CONSEQUENCES OF INADEQUATE FREQUENCY CONTROL DEVICES

During its development, SINCGARS had parallel efforts on slow frequency hopping and fast frequency hopping radios. Although fast frequency hopping was preferred, today, SINCGARS is a slow frequency hopping radio primarily because clock technology was not able to provide the low-power, high-stability clocks needed for fast frequency hopping. As a result, SINCGARS is much more susceptible to jamming than it would have been with fast frequency hopping. Today, we have the capability to jam slow-frequency-hopping radios such as SINCGARS; presumably, our adversaries will have similar capabilities in the future.

The Army radar system, SOTAS, was a coherent radar system that was to operate from a helicopter. In order to meet the phase noise requirement under the vibrations of the helicopter, an oscillator acceleration sensitivity of 3×10^{-12} per g was required. This was more than 100x better than the state-of-the-art. More than $100M was spent on this system by the time it was canceled. The system has been resurrected as Joint-STARS, operating from a modified Boeing 707. Although the vibration levels are now lower, the contractors have had great difficulties with obtaining the required low noise oscillators. During 1994, no bids were received in response to solicitations sent to more than 30 companies.

APPENDIX C - CURRENT DoD IN-HOUSE AND SPONSORED WORK ON CONTROL DEVICES

DoD – Ten years ago, all three services conducted significant frequency control programs, which were complemented by significant contractual programs. DoD labs' R&D has declined drastically during the past 10 years (by far more than the decline in the DoD budget), from more than 50 scientists and engineers working in-house, to about eight today, and from several significant contracts to none today.

As a consequence, most DoD frequency control R&D has been performed with specific program funds, driven by specific acquisition problems. The programs have been aimed at solving a narrow range of problems, often caused by system designers not understanding frequency control technology. The work is often performed by subcontractors to subcontractors. The results of the R&D are usually poorly documented and not distributed to either the government laboratories or to the general frequency control community.

The **Army's** 6.2 program is the only one remaining, but it is down to about eight researchers, a budget of about $1.2M per year, and no significant contracts. It is the only government laboratory working on small, low-power oscillators/clocks. The Army is the DoD lead service (Reliance Category III). Since the Army was assigned this role, the other service laboratories have not spent their 6.2 funds on frequency control technology. The Army, meanwhile, also cut its support of this technology area, from about 30 researchers and an extensive contractual program 10 years ago to eight researchers and no significant contracts today.

ARPA is funding a miniature atomic clock program at Westinghouse. This is currently the only significant DoD contract in frequency control technology.

NRL has been active in frequency control R&D, but currently has no 6.1 or 6.2 programs. Historically, it has specialized in the development of high-performance atomic clocks and platform time distribution systems. It currently supports the U.S. Naval Observatory (USNO), and performs test and evaluation of timing systems in support of DoD systems. Their work is usually customer funded and is tightly coupled to the needs of a particular project.

USNO, as the designated timekeeper for DoD, has been performing R&D to improve the U.S. Master Clock (which is the world's largest ensemble of the highest performance atomic clocks available), and to develop techniques for nanosecond accuracy worldwide time transfer. The level of (6.2) effort is about $400K per year.

ARO has been supporting a few basic research programs related to frequency control (mostly piezoelectric device related theoretical research).

AFOSR has been supporting a few basic research programs related to frequency control (mostly atomic clock related).

NIST has the largest frequency control program in the USA – aimed at advanced atomic clocks, time and frequency transfer methods, and characterization methods. Optically pumped cesium beam frequency standards, stored ion frequency standards, cesium fountain frequency standards, and optical standards are being investigated, with a long term goal of 10^{-15} to 10^{-17} frequency uncertainties or 0.1 to 0.001 nanoseconds per day time uncertainties. The level of effort is about 15 man-years per year, ~$3.8M per year.

NASA has been funding a frequency control program at the Jet Propulsion Laboratory, its lead center for time and frequency technology. The JPL program is aimed at developing frequency standards of the highest possible stability in support of NASA programs in space navigation, radio science, and astrophysics (e.g., gravitational wave and relativity experiments). The emphasis has been on the development of a trapped mercury ion frequency standard of 1×10^{-16} stability for periods of a few thousand seconds, and on photonic and cryogenic oscillators of exceptionally good short-term stability. JPL is also developing SAW sensors for humidity and payload-contamination monitoring. The level of effort is about 8 man-years, $1.4M in FY95.

The **Harvard-Smithsonian Center for Astrophysics** develops and builds advanced hydrogen masers primarily for scientific experiments, space tracking and navigation, radio astronomy, and international high precision time transfer. The goal is a stability of $<1 \times 10^{-15}$ per day. The level of effort is about 1½ man-years per year of research plus 6 man-years per year of hardware engineering and fabrication.

Coordination among the government researchers has been good, not only via AGED & JDL Reliance, but also because of the precise time and time interval (PTTI) coordination meetings at the Naval Observatory (which is for government only), the annual PTTI meeting (which is an open meeting, cosponsored by the Army, Navy, Air Force and NASA), and the IEEE Frequency Control Symposium and related IEEE activities.

APPENDIX D - UNIVERSITY ACTIVITIES, AND THE U.S. RESEARCH OUTPUT

No substantial research is conducted in frequency control technology at any single university. Individual professors with an interest in frequency control related subjects exist at about 20 universities. The largest activity is at the University of Central Florida, where four faculty members participate in a program aimed primarily at SAW device research and applications. Funding of the UCF program is derived primarily from small contracts with corporate sponsors (including Sumitomo of Japan).

The Army Research Office and the Army Research Laboratory have cosponsored theoretical research by individual professors at Rensselaer Polytechnic Institute, Princeton U. and Rutgers U. (<100K/yr. at each) which have been highly beneficial to the Army's experimental research programs, and which have produced a few Ph.D. graduates who are now employed by DoD laboratories and DoD suppliers.

The U.S. lags behind France, Japan, and other countries in supporting university research in this technology area. A single university in France, the École Nationale Supérieure de Mécanique et des Microtechniques, in Besançon, has more researchers working on quartz crystal devices than all the U.S. quartz device researchers combined. France has had a national effort aimed at making France the world leader in frequency control. The French government has been making major investments in both university and industrial research.

As there is a lack of college curricula in this field, training in the U.S. is primarily on-the-job, supplemented by short courses and tutorials offered annually by NIST and the IEEE International Frequency Control Symposium.

The decline in DoD support to university and industrial research, as well as to its own laboratories, has led to a significant decline in the proportion of research papers published by U.S. authors. U.S. authors used to dominate the IEEE International Frequency Control Symposium, (the major meeting of this field, held in the U.S. annually). Two years ago, for the first time ever, fewer than half of the papers were by U.S. authors. In 1994, fewer than 40% were by U.S. authors.

APPENDIX E - THE DoD MARKET AND THE INDUSTRIAL BASE

The total DoD frequency control market is estimated to be < $50M per year. The estimated U.S. frequency control market, and the approximate DoD percentages, are shown in Table 2. The numbers include components (i.e., resonators, oscillators, filters, and sensors) but not subsystems and systems. The numbers are estimates, as direct DoD procurement (by the Defense Electronics Supply Center, DESC) is primarily for repair and replacement. OEMs acquire the majority of components used in systems supplied to DoD, and the OEMs and component manufacturers treat parts usage and demand numbers as proprietary information. The DESC purchases about $4M of resonators and oscillators per year

Table 2 - Estimated Frequency Control Component Market

Technology	Units per year	Unit price, typical	Total market, $/year	DoD share of market (approx.)
H-maser	~ 10	$200,000	$2M	0 to 20%
Cesium	~ 300	$50,000	$15M	>75%
Rubidium	~ 8,000	$2,500	$20M	5%
Crystal	~ 1 billion	$1 ($0.1 to 3,000)	$1.2B	units: <<1% sales $: 2-3 M

The domestic industrial base, measured by both its absolute size and by its share of the worldwide frequency control market, has declined more than four-fold in recent years. While the world market more than doubled, the domestic manufacturing output declined more than two-fold. The low-end, high-volume business has been lost to Asian companies (e.g., the clock oscillators for watches, PCs, cars, etc.). The high-end (low-volume) business is primarily for DoD and NASA. As the DoD/NASA market has shrunk, the companies which specialized in supplying this market are no longer investing in developing capabilities and products for DoD/NASA applications; they have shifted their resources to the commercial markets.

The Air Force conducted an industrial base study of quartz crystal products in 1993. The conclusions and findings of this study included:

- Key C^4I defense programs rely on oscillators.
- Domestic capabilities/capacities to meet military requirements are eroding.
- Industry is moving off-shore.
- The industry supporting military needs is a shrinking, diverse group of resource constrained small companies.
- Government interests reside in diverse small departments or program offices.
- DoD is not focused on quartz crystal R&D.
- Companies' internal funding for research is limited.

- Growing industry view – 'DoD business is too costly/less profitable. Favor more profitable commercial orders.'
- Crystal oscillator problems tend to be treated on a program by program basis. Issues tend to be 'buried' down at vendor levels.
- In the U.S. there is no college curriculum to train new engineers in frequency control and timing device studies, while in Europe there are at least 26 colleges teaching courses and training engineers in this field.
- "Expect the trend to continue unless..."

A recommendation of the study was to "develop an interservice industrial base initiative to promote a stable supply base through process improvement and cost reduction".

The largest US producer is Motorola, estimated at $150M per year; its production is mostly for its cellular and mobile radio products. It is a captive producer, with much of its production performed in Asia. The next largest is AT&T, estimated at $50M per year, also mostly for internal use. Next, estimated at $20M to $30M per year, are: Datum, Saronix (with much of its production in Asia), Frequency Electronics, Hewlett-Packard, SAWTEK, Vectron, and RF Monolithics. Major foreign producers include Toyocom, NDK, Kinseki, Tokyo Dempa and Seiko (all are Japanese); Siemens, KVG and Tele Quartz (Germany); Thomson (France); Micro Crystal (Swiss); C-Mac (UK); Rakon (New Zealand); and low-end producers in Korea, China, Taiwan and Hong-Kong.

The DoD-relevant industrial R&D base has been disappearing in the U.S. The production base has also been shrinking because the DoD demand is not sufficient to support an adequate industrial base. Few companies are left to respond to DoD needs. The four major companies left are Datum, Frequency Electronics (which is currently disbarred), SAWTEK and Hewlett-Packard (which supplies only commercial devices, mostly high-end cesium standards for the Navy). Several small companies, with modest resources and run by entrepreneur-managers, have, in the past shown interest in the DoD market, however, most of these companies are no longer interested in this difficult and shrinking market. Illustrative of the lack of interest is the 1994 solicitation for the Joint-STARS master oscillator. No bids were submitted by any of the 30 companies solicited by Westinghouse-Norden. The specifications had to be loosened in order for the program to be able to obtain low noise oscillators needed for program continuation.

Small and uncertain production volumes discourage potential vendors. For example, even if the Joint-STARS production were fully funded, the total number of oscillators to be bought is one per system, i.e., 19 total, plus spares. Similarly, the total multi-year production volume for JTIDS is 140. In comparison, the total number of (medium precision) oscillators required for the world cellular and mobile radio market is about 60 million per year. DoD audit and procurement requirements are a major cost which also tend to discourage—especially the smaller vendors; the volume of business is often insufficient for vendors to have the incentive for maintaining the infrastructure required to do business with the DoD.

Appendix F - The STAR Agenda

Special Technology Area Review
on
Frequency Control Devices

March 21 and 22

Working Group A
Advisory Group on Electron Devices
Palisades Institute for Research Services
1745 Jefferson Davis Highway
Suite 500
Arlington, VA 22202

Tuesday, March 21

Session A - DoD Views

9:00 - 9:15	Introduction	Dr. Arthur Ballato, EPSD, ARL
9:15 - 9:45	C^3I and GPS requirements	Jules McNeff, OASD/C3I
9:45 -10:15	NASA views	Dr. Lute Maleki, JPL
10:15 - 10:30	Break	
10:30 - 11:00	Navy requirements & programs	Dr. Joseph White, NRL
11:00 - 11:30	Air Force perspective	Gerald E. Zahn, AF/Hanscom
11:30 - 12:00	Army/DoD requirements & programs	Dr. John Vig, ARL

Session B - Technology

1:00 - 1:30	Advanced atomic clocks	Dr. Donald Sullivan, NIST
1:30 - 2:00	High-end commercial oscillators	Dr. Leonard Cutler, HP
2:00 - 2:30	Hydrogen masers & other adv. tech.	Dr. Robert Vessot, Harvard SAO
2:30 - 2:45	Break	
2:45 - 3:15	Quartz (mass-produced) techn's	Juergen Staudte, XECO
3:15 - 3:45	Thin-film resonator technologies	Dr. Ken Lakin, TFR
3:45 - 4:15	SAW and DRO technologies	Dr. Gary Montress, Raytheon
4:15 - 4:45	Resonant sensor technologies	Roger Ward, Quartztronics

Wednesday, March 22

Session C - University and Industrial Base

9:00 - 9:15	Introduction	Dr. Arthur Ballato, EPSD, ARL
9:15 - 9:25	Industrial base activities	Dick VanAtta, OASD, Econ. Sec.
9:25 - 9:50	University activities	Prof. Donald Malocha, UCF
9:50 - 10:10	Break	
10:10 - 10:35	Material supply and demand	Gary Johnson, Sawyer Research
10:35 - 11:00	SAW supply and demand - military	Steve Miller, SAWTEK
11:00 - 11:25	Hi-end oscillators (DoD and NASA)	Martin Bloch, Frequency Electr.
11:25 - 11:50	Timing systems supply and demand	Dr. Samuel Stein, Timing Sol'ns

Wed PM - Discussion & conclusions (AGED and government personnel only).

APPENDIX G - ACRONYMS AND ABBREVIATIONS

AFOSR	Air Force Office of Scientific Research
AMRAAM	Advanced Medium Range Air to Air Missile
ARO	Army Research Office
ARPA	Advanced Research Projects Agency
ATRJ	Advanced Threat Radar Jammer
BAW	Bulk Acoustic Wave
C/A	Course Acquisition
C^3I	Command, Control, Communications and Intelligence
CVI	Code Validity Intend
DESC	Defense Electronic Supply Center
ELINT	Electronic Intelligence
FEM	Finite Element Model
GPS	Global Positioning System
IFF	Identification Friend or Foe
IR	Infrared
JDL	Joint Director of Laboratories
JPL	Jet Propulsion Laboratory
JTIDS	Joint Tactical Information Distribution System
MCXO	Microcomputer Compensated Crystal Oscillator
MILSTAR	Military Strategic Tactical and Relay System
NIST	National Institute of Standards and Technology
NRL	Naval Research Laboratory
NSA	National Security Agency
OCXO	Oven Controlled Crystal Oscillator
PGM	Precision Guided Munitions
PLL	Phased Lock Loop
PSK	Phase Shift Keyed
PTTI	Precise Time and Time Interval
P/Y	Precise Y-code
RMS	Root Mean Square
SAW	Surface Acoustic Wave
SINCGARS	Single Channel Ground and Airborne Radio System
SOTAS	Stand-off Target Acquisition System
STAR	Special Technology Area Review
STW	Surface Transverse Wave
TCXO	Temperature Compensated Crystal Oscillator
USNO	United States Naval Observatory
XO	Crystal Oscillator