The Lenkurt Demodulator

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Precise Frequency Control

Modern communications depend as never before on frequency and time standards of remarkable accuracy and stability. Precise time-keeping and extremely accurate frequency control are actually the same problem, since the accurate measurement of either time or frequency implies exact knowledge of the other. Although the basic principle of accurate timekeeping has been known for centuries, modern techniques have improved accuracy and stability many thousands of times. This article discusses some of these methods and how they are used in modern communications.

The precision demanded by a civilization or technology in measuring time and frequency is a good indicator of its state of advancement. Not very long ago, when communication as well as travel depended on ocean winds or beasts of burden, errors of a few minutes or even a few hours in a day mattered very little.

As the world and its affairs have grown more complicated, our need for better timekeeping has become much greater. Today our best time and frequency standards appear to vary only about one part in 10^{11} per month; if this error were to add up steadily in one direction (rather than occasionally cancelling), a clock controlled by such a standard would show less than one second error after more than two and a half centuries! More workaday quartz crystal oscillators have been built which drift less than one part in 10^{9} per month, or one second in two and a half years.

Although such stability seems extraordinary, it is not just precision for the sake of precision, or mere technical "showmanship." Many new communications methods now proposed will require time standards at least this good in order to function adequately. For example, the telephone network of the not-too-distant future is envisioned as transmitting many thousands of telephone and data channels through waveguide and other transmission means, in the form of millions—even billions—of pulses per second, and using time-division multiplex to keep track of each channel and its information. As the number of channels is increased (which is economically very desirable), the tiny intervals separating the pulses necessarily become shorter and are squeezed closer and closer together. Only if both the transmitting and receiving terminals operate at exactly the same frequency, and exhibit essentially no frequency drift can the information be recovered accurately. For large numbers of channels or long distances, it is very likely that this objective can be realized more easily by very stable free-running oscillators than by using the transmitted signal for synchronization.

Another application in which extremely precise frequency control will be required is a new type of international communications service using earth satellites. Frequency stability on the order of two or three parts error in 10^9 will be necessary in order to prevent distortion of the single-sideband, suppressed microwave carrier transmissions from the ground stations to the satellite, and this tolerance would have to be met by all the stations communicating through the satellite. This results from the fact that the 6000 mc radio carrier would not be transmitted, but would be reinserted at the satellite, and would have to match the carrier frequency of the ground stations within a very few cycles in order to avoid objectionable distortion.

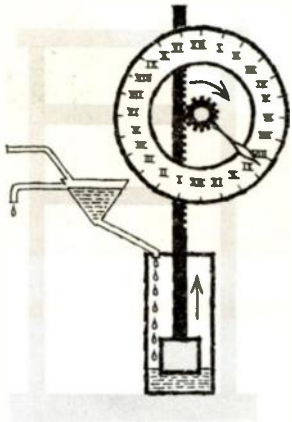


Figure 1. Early "clocks" used steady flow of liquid to mark time intervals. Device shown is refinement of simple graduated vessels from which water slowly escaped.

This is the counterpart of the problem in conventional frequency-division multiplexing systems which suppress the carriers of individual channels and groups of channels, but restore them at the distant terminals. As in the case above, serious distortion may result if the carriers provided at transmitter and receiver are not within a very few cycles of each other. Although this may be overcome by synchronizing the system with some sort of reference signal or pilot, it does not, however, eliminate the noise and distortion which results if the transmitted channels have drifted somewhat and no longer quite match the passband of the receiver filters. Frequency drift is more likely to be a problem in synchronous systems because oscillators of relatively low stability can be used, since they are easier to "pull" into synchronism and because they are cheaper.

Earlier Methods

From the earliest times, man has apparently been concerned with measuring time and dividing it into intervals to help him regulate his activities. Primitive methods of keeping time were based on the rising and setting of the sun and moon, and on noting the position of shadows of fixed objects. The sundial, however, was of very limited value, since it required sunshine and was therefore useless at night and in bad weather.

Early attempts to bypass this limitation were always based on the continuous flow of some medium—water or sand as a rule. Water clocks, or clepsydra as they were called, and the similar sand clocks marked the passage of time by passing the medium from one vessel to another in a regular way that could be used to define specific intervals. Similarly, the rate at which special candles or tapers burned also provided a rough indication of time intervals.

Figure 2. Other ancient methods of keeping time include calibrated candles and the hour glass, an offshoot of the clepsydra or water clock. Neither was noted for convenience or accuracy.

Around the year 1360 A.D. a major improvement in the basic design of timepieces appeared; the escapement, a means of changing a steadily-applied force into a reciprocating, periodic motion, soon became the basis for almost all timekeeping devices. These clocks were inherently faulty, however, since they had no basic time "consciousness." The rate at which they operated was entirely dependent on how much force was applied, the inherent loss or friction in the system, and the moment of inertia of the parts. Only the last item could be depended on to remain constant. Increased force would speed up the escapement rate, while bad lubrication would slow it down. Despite these shortcomings, however, the escapement was a great step forward, laying the groundwork for further improvements while providing better packaging and convenience than any of the various forms of clepsydra which preceded it.

The Discovery of Resonant Control

Galileo is said to have noticed that a lamp hanging in a church appeared to swing at a constant rate, regardless of the width of its swing, and suggested that this phenomenon might be used to measure time. Nearly a century later, Christian Huygens produced the first pendulum clock, immediately revolutionizing the art of timekeeping. At once the error in timekeeping was reduced from about 20 minutes a day to less than two.

The secret behind the new timekeeping technique was *resonance,* which still forms the basis of all frequency control. Resonance occurs in many forms—mechanical, electrical, or a combination

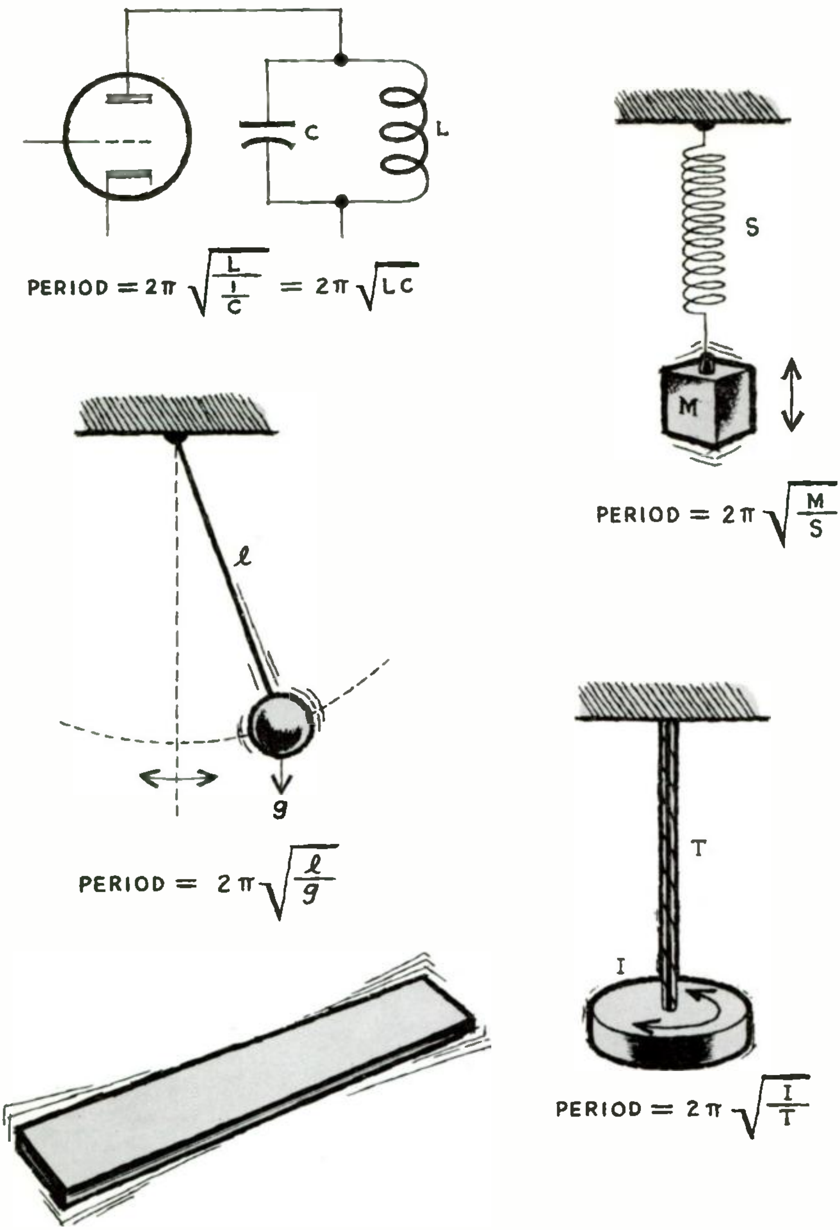


Figure 3. Several typical examples of resonance, and the basic relationships which determine frequency of oscillation. Note that all equations are essentially the same, save for the terms used. As long as these basic physical properties remain unchanged, frequency of oscillation remains constant. External forces and conditions, however, usually cause change, and must be overcome in stable oscillators.

of these. In all of them, the resonant element must have two essential properties—*mass* and *elasticity,* or their electrical equivalents. When the resonant element is deflected from its resting condition and then released, the elasticity tends to restore it to its former position. But when it reaches its resting position, inertia carries it by until the elasticity arrests it and again turns it back toward the resting position. This continues until various losses in the system finally use up all the energy supplied by the original deflecting force.

This type of oscillation is very obvious in the pendulum, the tuning fork, and various mass-and-spring combinations, but is also present in tuned electrical circuits, piezoelectric materials, and even in molecular and atomic particles. Figure 3 diagrams some familiar examples of resonance and the basic relationships which control their resonant frequency. In all of these resonant systems, it is vital that the "circuit constants" do not change if the frequency of oscillation is to remain constant. For this reason, a pendulum will change its period if either its length or the local force of gravity changes. Thus, if a pendulum rod is made of a temperature-sensitive material such as steel or copper, the lengthening of the rod with higher temperature will slow the pendulum about ½ second per day for each °C change. Similarly, a pendulum clock that keeps accurate time at ground level will lose more than a second a day at the top of a tall building, due to the slight reduction in the force of gravity. In the case of electrical resonance, slight changes in either capacitance or inductance will change the resonant frequency. These changes might be caused by the effect of temperature on the capacitor's dielectric constant, or on the magnetic permeability of the inductance.

Effect of Q on Stability

A very important factor in determining the accuracy and stability of a resonator is its Q or quality factor. In general, the Q of a resonator is directly proportional to its freedom from loss. Thus, the higher the Q, the less power that must be supplied to sustain oscillation. When the Q of a device is low, more power must be added. This unavoidably "smears" the frequency of oscillation and contributes to instability and drift. Thus, the higher the Q, the more stable the resonant frequency. A resonator of infinite Q would oscillate indefinitely and would exhibit perfect frequency stability.

Due to resistive losses, Q's on the order of only 150-200 are typical of electrical resonant circuits. Resonant cavities and transmission lines normally achieve a Q of a few thousand, while the Q of a good pendulum will range from 10,000 to 100,000.

Quartz Crystal Resonators

Among the best man-made resonators yet developed are plates, bars, or other shapes cut from quartz crystals. The quartz crystal resonator, developed about 1922, has proven to be the most versatile and dependable resonating device yet produced. Carefully prepared quartz resonators have demonstrated a Q of 5,000,000, although this class of performance is available only from certain special cuts which operate at relatively high frequencies. Only recently has the accuracy and stability of the best quartz resonators been substantially

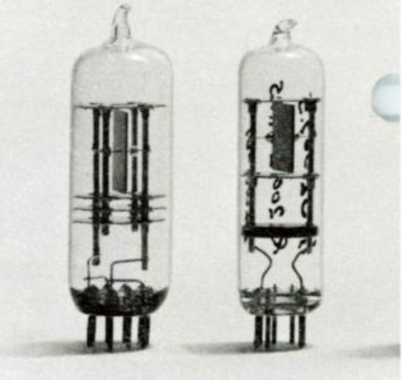


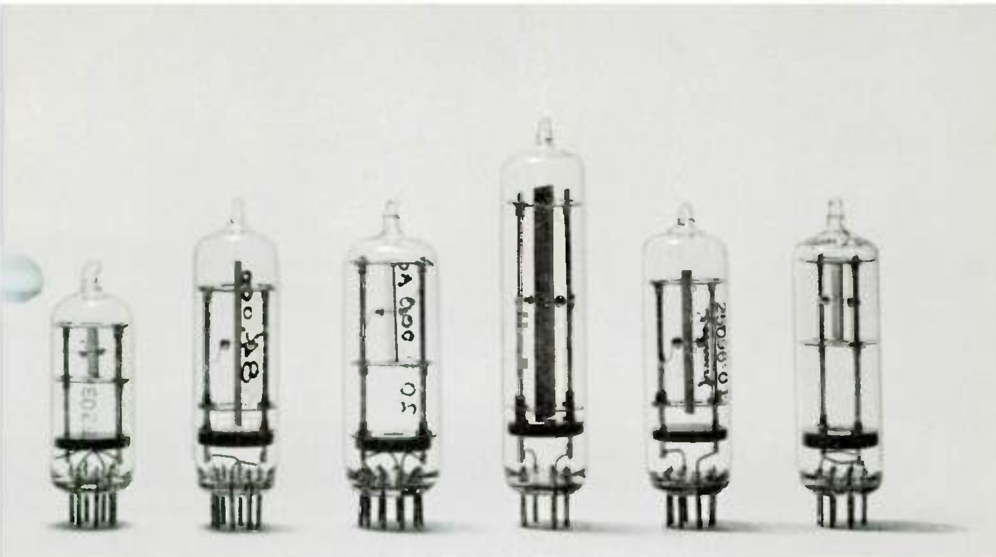
Figure 4. Modern quartz crystal resonators for multi-channel carrier systems. Size, shape, and proportion determine resonant frequency and other properties. Angle of cut relative to crystal structure, is also very important in determining frequency and temperature characteristics.

exceeded, and then only by so-called "atomic clocks", rather complicated devices which use atomic resonance for their control element.

Quartz appears to be very nearly ideal for use in resonators. Although almost all materials suffer internal losses from internal friction or elastic hysteresis, most if not all of the loss in good quartz crystals appears to be caused by minor surface irregularities and the effect of mounting. Very tiny amounts of surface contamination have been shown to reduce quartz crystal Q by one-half! A good comparison of the effect of Q on resonator performance can be made by noting how long the device will vibrate when no additional power is supplied. Although a good tuning fork vibrating in a vacuum can sustain about 2000 cycles before the amplitude of vibration is reduced to half, and a high-Q electrical circuit about 100 cycles, well-mounted quartz crystals have been able to "coast" more than a million vibrations before reaching half amplitude.

Quartz is unusually stable, mechanically and chemically, so that it is generally unaffected by almost any conditions to which it may be subjected. In addition, quartz has a very low temperature coefficient of expansion, thus reducing temperature effects. Strangely, quartz slabs cut from the crystal at a certain angle will exhibit a *negative* temperature coefficient, while slabs cut at another angle may have a positive coefficient. By carefully choosing the angle of cut, it has been possible to produce crystals having essentially a zero temperature coefficient over the range 0-100° C. Unfortunately, this cut (the "GT") is limited in the frequency range available and is expensive. Accordingly, other cuts are more frequently used, according to the mechanical and electrical properties of the finished crystal most desired. Figure 4 shows some of the quartz crystals manufactured at Lenkurt for use in Lenkurt carrier equipment.

Despite the high Q available from



quartz units, resonant frequency is sensitive to crystal current (a function of driving power) as well as temperature. Temperature and driving power also affect crystal *aging,* a change in operating frequency which is relatively great when the crystal is new, but which declines with time. Aging is apparently caused by local surface imperfections introduced during fabrication, migration of material between electrodes and leads, and the "shaking out" of microscopic contaminating substances. Once the initial crystal aging period is passed, it is important to restrict crystal activity, and all precision oscillators use some form of current limiting to stabilize crystal operation.

Temperature Control

Despite the inherently low temperature coefficient of quartz, the frequency stability required may be so great that crystal operating temperature must be carefully restricted. As shown in Figure 5, the temperature-frequency charac-

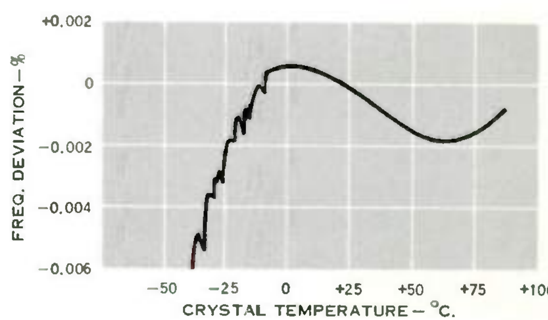


Figure 5. Temperature-versus-frequency characteristic of crystal designed for overtone or harmonic oscillation. Irregularities in left portion of curve are spurious modes of oscillation. Note "turning point" at about 60°C.

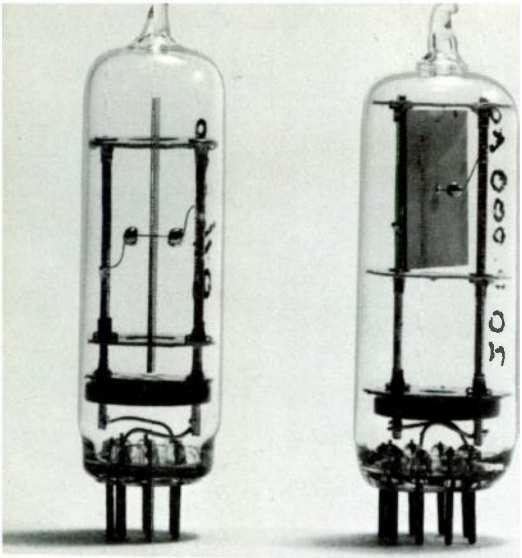


Figure 6. Extreme care is required in mounting crystals. Leads are soldered to gold coating at exact nodal point of vibration. Solder beads damp vibration in leads, should be located an odd number of quarter-wavelengths (at resonant frequency) from crystal.

teristic of crystals is not uniform, but changes according to temperature. Note that the temperature characteristic reverses direction at about 60° C. Over a very narrow range of temperature in this region, temperature has a minimum effect on frequency. This point of "zero" temperature coefficient is sometimes called the "turning point" of the crystal, and can be varied by slight changes in the angle at which the crystal is cut.

In order to take advantage of a crystal's zero temperature coefficient, it is usually operated within an insulated, temperature-controlled "oven." This will usually consist of an insulated enclosure having a high specific heat (requiring a large number of calories to change the temperature a small amount) and a temperature-controlled source of heat.

Where stability requirements are not very strict, an on-off thermostat may be used. Ovens of this type can be designed to maintain the temperature constant within a few tenths of a degree. This type of temperature control has the merit of simplicity, but permits relatively large excursions of temperature, since a definite temperature change must be detected before heater power is turned on or off. Nevertheless, a high degree of frequency stability may be achieved, depending on the type of crystal used.

Proportional Control

A more refined technique is the use of *proportional* temperature control. Proportional control has been known for many years but used very little except where utmost temperature stability was essential. Its use is now growing because reliable transistor circuits make it more convenient, and because the need for improved frequency stability is becoming much greater.

In this method, instead of turning a heater on and off (so that oven temperature swings above and below the desired temperature), heat is introduced continuously, but is continuously varied to

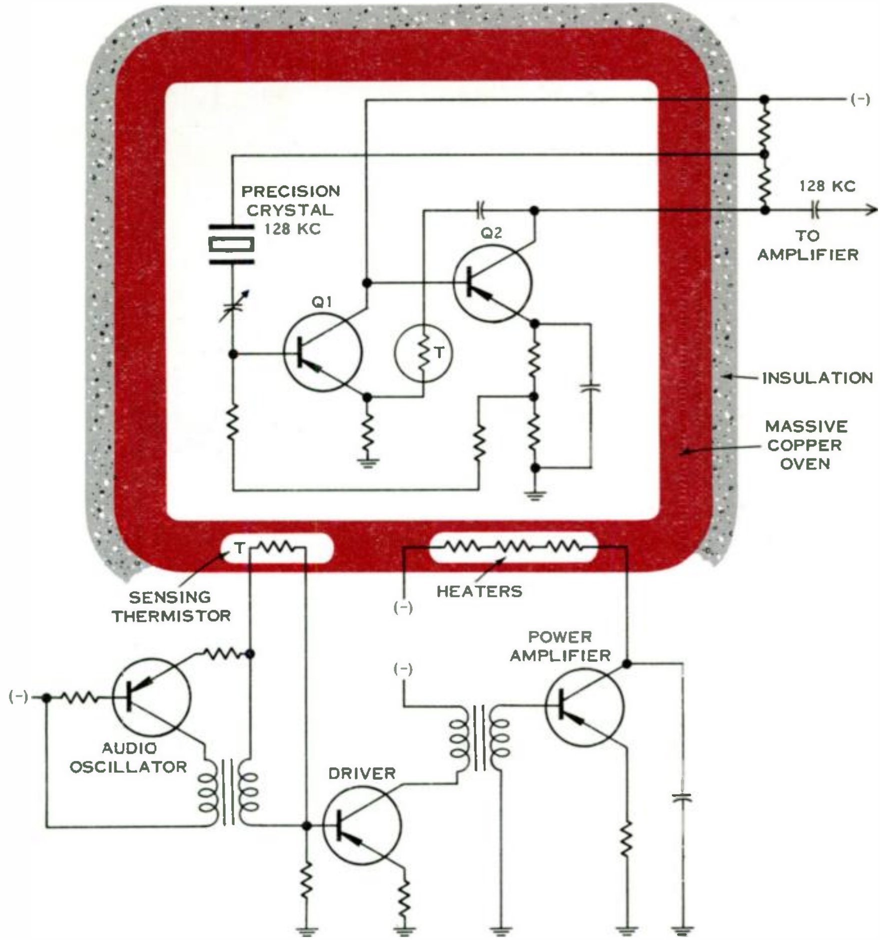


Figure 7. Simplified schematic diagram of Lenkurt 46A Master Oscillator and proportional temperature control oven. Crystal oscillator is thermistor-limited to maintain stable output. Temperature change in copper oven wall is sensed by thermistor which continuously varies audio oscillation and the amount of current supplied to oven heaters.

match the heat lost by the oven.

Figure 7 shows a simplified schematic diagram of the master oscillator and its proportional temperature control circuit used in the Lenkurt Type 46A Carrier system. The 128-kc output from this oscillator is used to derive all channel, group, and supergroup carriers for the 600-channel system. In order to avoid effects of temperature variations on transistor performance, the entire oscillator circuit is enclosed within the oven.

The thermistor (temperature-sensitive resistor) shown in the feedback path from Q2 to Q1 acts as a "governor", holding oscillator activity and crystal current to a very constant value.

The oven itself is a massive copper block into which holes have been drilled to hold the oscillator, heating resistors and sensing thermistor. The sensing thermistor is connected into an audio oscillator circuit in such a way that if oven temperature drops slightly, oscillator feedback increases, thus driving the power amplifier harder and drawing more power through the heating resistors which comprise its load. In this particular design, crystal temperature is maintained within .01° C over a 60-degree range of ambient temperatures; the 128-kc output drifts less than 1/50 cycle in three months if error adds up in the worst way.

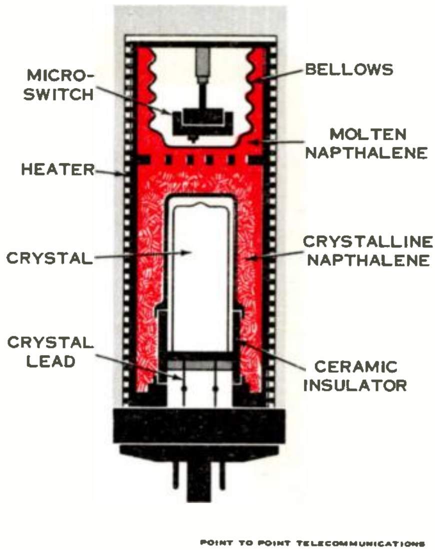


Figure 8. Napthalene in change-of-state crystal oven is kept in half-molten, half-solid state to maintain near-perfect temperature stability. Bellows and microswitch control heat by sensing expansion and contraction of napthalene.

Change-of-State Oven

A recently-developed crystal oven provides what may be the ultimate in temperature control — essentially zero temperature change. Even excellent proportional control ovens must exhibit some temperature differential, since an "error signal", no matter how tiny, must be present before heater power is altered. In the change-of-state oven, however, no temperature differential at all need exist except for the heat lost through the electrical leads to the crystal.

This device takes advantage of the fact that the melting and freezing temperatures of crystalline substances are identical, and that the change from the solid to the molten state is dependent on the *heat* stored in the material, rather than its temperature. Water, for instance, requires about 80 calories per gram to melt. When both physical states are present, the temperature remains exactly at the melting point until the material is either melted or solidified. If a substance is chosen which expands or shrinks when going from one state to the other, it becomes possible to detect changes in the heat content of the system before there has been any change of temperature. As the substance cools and contracts (expands, in the case of water) a bellows and switch activates the heater, thus restoring some of the material to the molten state, still with-out a change of temperature.

In one such device, napthalene (also used in "mothballs") was the substance chosen. Napthalene melts at 79.5° C and requires about 36 calories per gram for fusion. In this particular oven design, temperature variation within the oven was found to be ± 0.0014° C.

Atomic Timekeeping

Until a few years ago, most national frequency standards consisted of extremely stable quartz crystals located in temperature-controlled vaults. Today, these have been replaced by cesium beam "atomic clocks" which maintain stability on the order of one part in 10^{11}, or about two parts in 10^{12} over a few hours. These standards use the resonance of cesium 133 atoms in making quantum transitions between energy states (see DEMODULATOR, *July,* 1961 for a discussion of quantum resonance). The cesium resonance frequency in these standards is 9,192,631,770.0 cycles per second.

Other ultra-stable atomic resonators have been developed which are both simpler and possibly more stable than the cesium beam standard. One such development is the rubidium vapor cell, which has a Q of 170,000,000, more than twice that of the cesium resonance. The rubidium cell is not really as suitable for an absolute standard of frequency as the cesium beam because the resonant frequency can be altered slightly by the way the device is constructed. Once built, however, it is fantastically stable. Several rubidium gas cells built for use in satellites have shown less than one part drift in 10^{11} per month over a period of a year, about 1/30 that of a cesium standard with which they had been compared.

Oscillators capable of accuracies in this range are certain to become relatively simple and cheap, thus permitting their widespread use in many old and new communication applications, particularly ultra-high-speed data transmission and satellite communications. The stability and cost of conventional communications equipment will benefit and its information-handling ability can be expected to increase. •

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