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## ACCURATE TIME MEASUREMENT

*by* Dr. FREDERIC A. FUA,
Director of Research
Standard Electronic Research Corporation

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11 West 42nd Street ★ ★ ★ New York City

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# ACCURATE TIME MEASUREMENT

by Dr. FREDERIC A. FUA,
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The latest techniques in communications and radar are demanding ever increasing accuracy in the generation and measurement of radio frequencies. This paper will discuss some of the latest advances in primary frequency standards, achieving accuracies thought impossible a few years ago.

At the beginning of every science there is a practical need. It is later, much later, that pursuit of science becomes an end in itself. A few more centuries and science again becomes utilitarian and accepts being hitched to industry's wagon and become a means, first to develop, then improve, the tools or the toys of HOMO SAPIENS: cars, radios, refrigerators, airplanes, vacuum cleaners and the like.

At the beginning of geometry and trigonometry there probably was the need to determine the exact boundaries of each property and the means to set the boundary stones back to their original place had they been displaced by accident or cunning.

This happened probably when our forefathers abandoned their nomadic life and settled down to cultivate the land and raise their herds. Probably about the same time, give or take a thousand centuries, the need was felt for accurate time determination to fix the time for planting, harvesting, etc.

Whether these early marks in the flight of time were purely lunar, (about 12 moon years for one of our years), lunisolar or solar will probably never be known inasmuch as the art of time keeping was most likely many milleniums old when the first zodiacs were painted on, or engraved in, stone.

Whether the relative inaccuracy of the first signposts on the time continum or our ignorance as to their exact duration may explain the abnormally long, by our experience, life-span of the first biblical figures, is another moot question, but this indicates the necessity of a time base which can be readily checked and reproduced. We shall come to this later on.

The sundial, the hour glass, the clepsydra, etc., were the answers to the need for breaking down the day into smaller intervals, but not until Galileo (circa 1600 A. D.) discovered the isochronism of small oscillations of a pendulum, was it possible to build accurate time keepers.

By the end of the 18th century these had reached a high degree of accuracy and were used for longitude determinations. The scientists accompanying Napoleon in his mid-west expedition determined the geographical position of a few selected spots in Egypt.

Over 50 years later another determination was made by a British party who found an appreciable difference from the previous results.

For those who think this disparity in position was to have no practical value other than for pure science, history refers us to a still later period when the discovery of oil in the Sinai peninsula raised the question of the legitimate owner of a piece of property. The estate boundaries were shown as extending from so many degrees, minutes and seconds of arc east of Greenwich to so many other degrees, minutes and seconds, and whether the late 18th century determination or the mid-nineteenth was correct made all the difference between affluence or nothing. The earlier physicists were right and title to the property was transferred to a neighbor. That rich oil man no doubt appreciates the part longitude and indirectly time, played in his unexpected wealth.

The story was told to me about 1920 by Dr. Fourteau, an eminent geologist in the service of the Egyptian government, but the following was witnessed by me personally:

Whilst a young man I spent some time in Egypt where I numbered among my acquaintances, a Major in the British Army. (I am sure you all know of the proverbial stiff-backed, upright colonial Army). One day, having been invited to lunch, I was amused to have the Major raise his hand very importantly, shushing me whilst regarding his watch with strict attention. As his watch showed the stroke of 12, he dropped his hand, and gave the signal for the sounding of the noon time cannon.

When he explained that this was a very important event I asked him what would happen if his watch were wrong. Upon this he explained that in the village there happened to be an expert watchmaker, trained in Switzerland, in whom he had full confidence. This seemed perfectly reasonable to me until a few days later when my watch needed cleaning. Finding myself in the village near this paragon of watchmakers, I approached his shop only to find the old man himself, standing in the doorway of his shop, with his watch held to the light so that he could--(yes, you guessed it) set it to the correct time by the sound of the noon cannon. --Talk about the blind leading the blind!

The improvement of the time pieces, at first very rapid through the 17th and 18th centuries, slowed down its pace until it reached almost a stand-still towards the close of the 19th century. Improvements were made from time to time, such as the use of a hair spring made from a metal with a low temperature coefficient to minimize the influence of temperature variations; the use of non-magnetic materials; better bearing surfaces; change of shape of the teeth of the escapement wheel etc., but despite the fact that entire lifetimes were devoted to this task, it was obvious that there was little to be hoped in the way of major improvements along existing lines.

A major breakthrough in time measurement had to wait forty years following the discovery of the piezo-electric properties of quartz and other materials by Pierre and Jacques Curie in 1880, and the invention of the three-electrode vacuum tube amplifier after the turn of the century. The pioneering work in this field was done by A. M. Nicolson and W. G. Cady, followed shortly afterwards by G. W. Pierce.

Successive improvements due to many scientists both here and abroad led to the development of crystal oscillators, stable to fifty parts in a billion, equivalent to a change of slightly more than a second a year. Basically this appears to be the upper limit which can be expected from quartz controlled oscillators. There does not seem to be any way to improve this limit by modifying the network connecting the tube and the resonant circuit, because under present conditions any increase in the effective mutual conductance means an increase in capacitance variability.

It appeared that again a dead end had been reached and that a new approach was necessary.

To get a clear picture, a short analysis of the operating conditions of a crystal oscillator is mandatory.

In a very general way we can say that the operating frequency is that frequency for which the sum of the phase angles of all the components in the frequency determining circuit is zero. Conversely, therefore, the frequency stability depends upon the phase stability of each component of the two main elements of the oscillator's network, the resonator and the electronic system which behaves as a negative resistance.

The resonator has been successfully made extremely stable in phase, but the phase stability of the electronic system under the best possible conditions, leaves much to be desired. This stability depends essentially upon the tube geometry, the space charge capacitance etc., and those factors cannot be made stable enough to keep the phase instability of the negative resistance to $10^{-5}$ radians, which is the value required if the frequency instability due to the electronic circuit is to be kept below 1 part in 100 billion.

The solution therefore is to entirely eliminate the villain, the thermionic tube, at least from such parts of the circuit where its variability will play havoc with the frequency.

Basically the frequency variations of the signal are converted into amplitude variations using a stable resonant circuit as reference. This can be achieved either by comparing the response of one single resonator to two frequencies, or of two resonators to one single frequency.

Lately equipment has been developed along similar lines except that the error signal is generated by the comparison of a single frequency and a single resonator. This system will be rapidly described because of the elegance of the solution although it is already being superseded despite the fact that the stability has been improved by a factor of more than 10 over previous equipment and equals present atomic clocks.

In this circuit, the quartz crystal used to determine the frequency of an oscillator, forms one arm of a reactance bridge. The reactance of another bridge arm is varied so that the bridge attains symmetrical states of unbalance about a null point. A slight variation in oscillator frequency will radically change the crystal reactance so that the bridge will now vary asymmetrically about the null point. The asymmetrical output thus produced is used to drive a servo controlled variable reactance to cancel the oscillator's reactance changes, thus holding the oscillator frequency very close to the crystal's resonant frequency despite considerable parameter variations. The stability claimed is of a few parts in 10 billion per week, which is as good as a molecular time clock.

Whichever way we look at it, however, the fact remains that all we can hope is to reduce the variation in crystal frequencies. But under the best possible conditions there are tiny shifts which remain and these are superimposed over a steady change with age. This is a serious theoretical limitation and nothing can be done about it.

Moreover, if all standards were suddenly destroyed and the length of the year changed by a cataclysm, they could not be duplicated. This weakness of all standards which rely on a prototype of some kind is well known. It is for this reason for instance, that the unit of length which was originally the distance between two lines engraved on a platinum bar, has been replaced, first by the wavelength of the cadmium red line (around 6438 Å) next by the green line of Mercury $^{198}$ (around 5460 Å). For this same reason, it is necessary to find an invariable unit of time.

Shortly after Curie observed that the disintegration rate of Radium could not be changed by any known method, that it was a truly molecular constant, he suggested the half-life of Radium (about 1590 years) as an absolute time constant. Although very sound in principle, this particular constant was not a practical one. But it was a step in the right direction: in some way the unit of time should be related to an inveriant property of the molecule or atoms.

The various atomic clocks meet that requirement: the motions of atoms and molecules which can be used as pendulums are absolutely pure and regular, their rates are fixed by laws of the atomic world, and it is inconceivable that even our inept manipulation of atomic power, while it may eventually change the face of this planet, could change the governing atomic laws,

The same vibration which had been used to determine the unit of length, the green line of Mercury $^{198}$, could have been used to determine the unit of time; the unit of length by the distance between two successive peaks or troughs, the unit of time by the number of vibrations of this specific wavelength in an arbitrary time interval: 1 second.

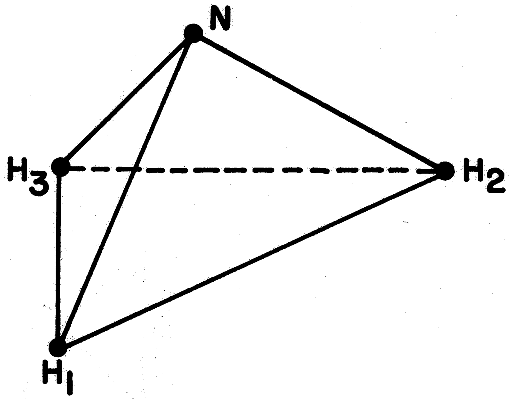

Figure 1

The vibration of the electrons that radiate visible light are much too rapid to be counted, but there are atomic oscillations with frequencies of a few billion cycles per second which can be accurately counted by existing techniques.

The first atomic clock devised used the ammonia molecule, which is shaped like a pyramid with three hydrogen atoms at the corners of the triangular base, and one nitrogen at the apex. (see Fig. 1)

Experiment has shown that the ammonia molecule can, however, invert itself with the nitrogen atom passing through the triangular base and come out to an apex position on the other side. This type of vibration gives rise to its microwave spectrum. The inversion frequency of the molecule depends on its rotational state which is described by the quantum numbers, J and K. (1.)

From general principles of quantum mechanics, J and K must be integers. Of the series of inversion lines characterized by different values of J and K, the 3-3 line at 23,870.140...Mc/s is the strongest and has, therefore, been selected as reference.

Whenever excited, the ammonia molecule starts to vibrate if the exciting frequency is:

1) equal to one of its characteristic frequencies.
2) of sufficient amplitude

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(1) J is the magnitude, in units of $h/2\pi$ of the angular momentum of the molecule excluding nuclear spins; and K is the projection of the vector J on the molecular axis of symmetry.

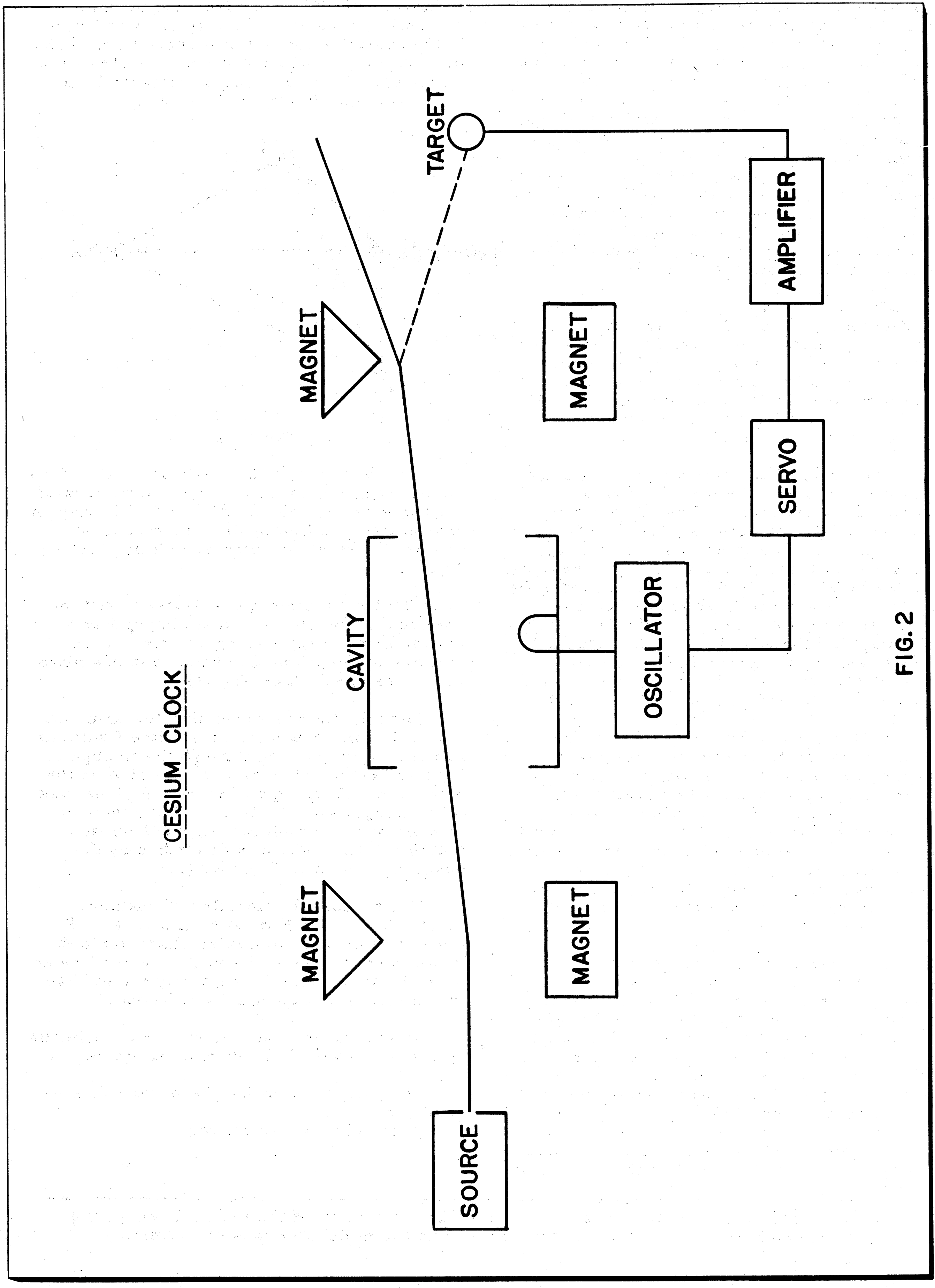
CESIUM CLOCK

FIG. 2

At 23,870...Mc/s there is considerable absorption of energy by the nitrogen atom, and this was used to build the first atomic clock.

This was essentially a quartz oscillator set to oscillate at a frequency which was a submultiple of the 3-3 line at 23,870 ...Mc/s. This fundamental frequency, multiplied electronically, produced a signal at a frequency close to that of the ammonia molecule. This signal was fed at one end of a waveguide several feet long filled with gaseous ammonia and terminated at the other end by a receiver.

If the signal frequency is equal to the ammonia frequency, most of it will be absorbed. On the other hand, if the signal frequency is slightly off, most of the energy will reach the receiver. The signal thus created is fed back to the crystal as a correction factor, using well known servo-techniques, to change the crystal frequency, and bring its $n^{th}$ harmonic to the ammonia absorption frequency.

The original equipment built by the Bureau of Standards, showed a variation of less than 3 parts in 10 million over a 15 hour interval, and less than 1 part in 10 million in any one hour interval.

An improved version is stable to within 1 part in 100 million, and J. Rossel in Switzerland, and K. Shimoda in Japan have reported stabilization of 2 to 3 parts in a billion.

Although very impressive, there is little hope to be able to do better by this method because of two serious limitations which are inherent to it. First the moving molecules are continuously colliding with each other and the walls, and their atoms are therefore subjected to outside forces which slightly spread the molecule frequency from its normal value. The next villain in the picture is the well known Doppler effect which changes the pitch of a locomotive whistle and probably is causing the red shift of receding nebulae.

For the microwave passing through the wavequide, gas molecules moving in the same direction appear to vibrate at a slightly lower frequency than they actually are; and the molecule frequency appears to be slightly higher if they travel in the opposite direction than the waves. This causes a certain fuzziness, or a spread, around the center frequency and thus limits the possible accuracy of this type of ammonia clock.

In this constant fight for one more decimal point, the next best atomic clock has been built around the cesium atom. The cesium atom has a natural vibration at a frequency which is in the microwave region around 9192 Mc/s and it is an atomic process and not a molecular one as in the case of ammonia.

Cesium, which belongs to the alkali metal group, has a single electron in its P shell. The spin of this single electron makes a magnet. Its spinning nucleus is another magnet. Neither magnet is spinning in a rigidly fixed direction but rather wobbles around a fixed line.

Whilst the earth pole precession occurs once every 26,000 years, the cesium precession occurs over 9 billion times a second, and this makes the cesium clock 'tick'.

We have seen, in the ammonia clock, the nitrogen atom flip spontaneously back and forth through the plane of the three hydrogen molecules, and so more so when properly excited. Similarly when the cesium atoms are excited by a microwave field oscillating at 9192 Mc/s, the outer electrons can flip over in a new direction and present different electromagnetic characteristics.

In the cesium clock instead of having, as in the ammonia clock, an electromagnetic wave travel across the absorbing medium, we have a stream of gaseous cesium travel in a waveguide between a source which is a small aperture in the wall of an electric furnace electrically heated to vaporize the cesium, and a target several feet away, which is a straight piece of wire. (see figure 2)

In the first section of this long waveguide, the cesium beam is submitted to the action of a magnetic field. In the next section, it comes under the influence of a microwave field of a frequency of about 9192 Mc/s, and finally it passes through a second magnetic field similar to the first one immediately before the target.

Now let us examine how this set up discriminates between the atoms which have or have not experienced a transition when passing through the center part of the waveguide in the microwave field.

We already know that the two groups of particles, excited and unexcited, can be distinguished from each other by their magnetic dipole magnetic moments. When submitted to a strongly unhomogeneous static magnetic field, they are deflected in different directions.

Let us follow now an unexcited atom on its way through the waveguide. It enters the first unhomogeneous field and gets deflected as shown. When it passes through the microwave field and the frequency of the field is not the correct value, nothing will happen to it. On entering the second unhomogeneous magnetic field, it will be deflected once more in the same direction and therefore will miss the detector wire.

If however, the frequency of the microwave field has the correct value, our atom will absorb energy from the field and will become an excited atom with reverse magnetic dipole polarity so that it gets deflected back towards the axis by the second magnetic field, and therefore hit the hot wire.

Similar reasoning will show that excited atoms when entering the first magnetic field will be deflected upwards, will release their excess energy to the microwave field in the center cavity, and become unexcited, whereupon they will be deflected downwards in the second field. Inasmuch as the two deflections cancel each other, they will again hit the hot wire.

The detector, as we can see, counts the particles which have experienced a transition in the microwave field regardless of the direction of transition, from excited to unexcited or vice versa, and therefore does not load the cavity appreciably.

In the original model, this detector, a hot wire, ionized the cesium particles which were picked up by a mass spectrometer.

In the industrial model the ionized particles hit the cathode of an electron multiplier and the cesium input current is amplified a million times.

In both cases the output current is proportional to the number of molecules which have undergone a transition.

As we have seen this depends on whether the field in the cavity was at the right frequency or not, and therefore can be used to adjust the frequency of the exciting field using well known servo techniques.

This system has several advantages over the ammonia clock previously described. The cesium clock is extremely accurate because the spectrum line is very sharp inasmuch as the device eliminates collision between atoms and the Doppler effect which broaden the absorption in the ammonia clock. There is no Doppler effect because the microwaves attack the beam at right angles instead of moving along the same line of travel.

The stability achieved so far either at the National Physical Laboratory in England by Dr. Essen, or in this country with the National Company's Atomichron, is about 1 part in a billion which is about one power of ten worse than the quartz servo control of the Marconi Instrument equipment analyzed earlier. It is expected however, that with proper care, a stability of 1 part in 10 billion will be achieved which corresponds to a change of 1 second in 300 years.

From certain tests it appears as if there are some sources of frequency changes which so far have not been explained. (A change in magnetic field or a change in the power fed to the cavity). The first is not objectionable where there are no stray magnetic fields and there is no difficulty in keeping the input to the cavity constant. For the sake of completeness I though it necessary to bring this to your attention although the change is only a few parts in 10 billion.

Instead of using the fact that certain frequencies are absorbed by ammonia gas, which was the determining element of the ammonia clock previously described, Townes, Gordon and Ziegler of Columbia University used the same property in a different manner which avoids the weak points described earlier and produced a frequency standard of the highest stability reached so far.

To get a clear picture of the operation of the MASER (a word coined by the Columbia group which stands for Microwave Amplification by Stimulated Emission of Radiation) a short touch of quantum physics is essential.

In any gas, the atoms and molecules can possess different amounts of energy which are determined by their electron configuration. In general, this energy is not an arbitrary figure but a well defined amount which corresponds to definite sets of configurations called "stationary states". These allowed energies are at narrow discrete levels separated by ranges of unallowed energies.

Under certain conditions, an atom in one state may interreact with its environment, thus losing or gaining a certain amount of energy to make a transition to another state. The quantity of energy exchanged in this transition is equal to the difference of energy of the two states. The probability for upward transitions between a given pair of states is identical with the probability for downward transitions.

When a gas is in thermal equilibrium, the number of atoms in the $i^{th}$ states is proportional to $_{e}$-$E_i$/kT where $E_i$ is the energy of the $i^{th}$ states, k is the Boltzman constant and T the absolute temperature. Therefore, there are always more molecules in the lower level than in the upper. If such a gas is irradiated by microwave at one of the transition frequencies, invariably a net absorption of energy takes place.

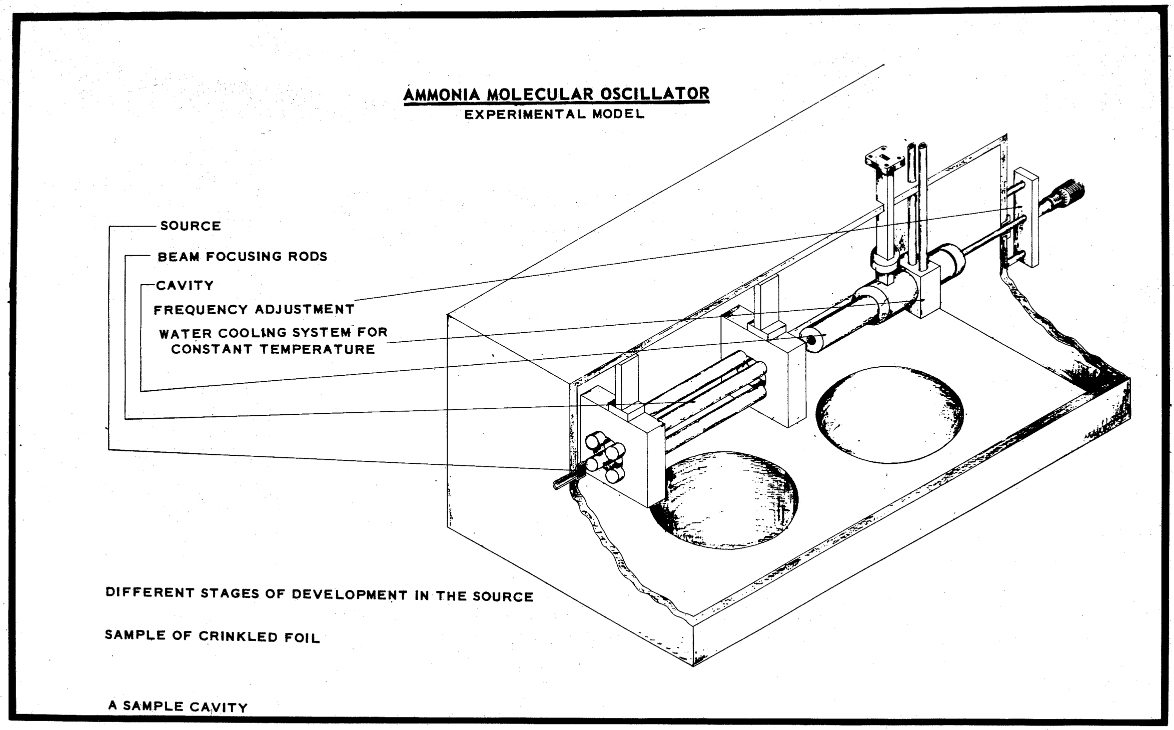

Figure 3

If, however, one could isolate all the molecules which are in the higher energy state, and then irradiate them, there would be a net loss of energy by the molecules to the field and the exciting microwave signal will be amplified, this because of the very general thermodynamic law that $P_{ab}=P_{ba}$ the probability for a transition from state 'a' to state 'b' is equal to the probability of the inverse transition from 'b' to 'a'.

Such an isolation of molecules in higher energy state is accomplished in the following manner. (see figure 3) A highly collimated beam of ammonia molecules is made to pass axially through an array of parallel rods which describe a cylinder about this axis. Each of these rods is alternately positive and negative. With this geometrical set up, a radially inward force is exerted on molecules in the upper inversion state and a radially outward force on the molecules in the lower inversion state. Therefore, for the collimated beam of ammonia molecules, this set up acts as a converging lens for those in the upper state, and a divergent lens for those in the lower state. Finally at the remote end of this focusser, there emerges a beam of molecules virtually all in the upper inversion states and they enter the cavity which is resonant at 23.870... KMc/sec.

It is obvious from the foregoing that transitions occurring in the cavity will, on the average, release more energy than they will absorb, and if this total energy released is higher than the electrical losses in the cavity, a steady output will be obtained and the set up will act as a generator, the frequency of which is determined by the molecules.

Since the radiation emitted is coherent (has the same phase, direction and polarization) with the exciting radiation, the oscillation is highly monochromatic.

Since the frequency of oscillation is determined primarily by the difference of the energy levels of the ammonia molecules, there is little frequency difference due to macroscopic changes in the Maser. The frefrequency of such an oscillator has been observed to have a random drift of only one part in $10^{13}$ in a period of 2 hours.

Whether engineering techniques finally ordain the cesium or ammonia approach it seems certain that the atomic standard will be useful in the solution of problems involving long periods of time, such as the irregular changes in the speed of rotation of the earth.

It will be useful in studying further the annual variation although quartz has already revealed the essential features.

Probably the most important problem still to be solved is whether the atomic and gravitational time scales are different.

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| 80 | 2 Mc to 400 Mc |
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| 84-TVR | 400 Mc to 1000 Mc |
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| 210-Series | 25 Mc to 200 Mc |

## SQUARE WAVE GENERATORS

| MODEL | FREQUENCY RANGE |
|---|---|
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|---|---|
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| MODEL | FREQUENCY RANGE |
|---|---|
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| MODEL | FREQUENCY RANGE |
|---|---|
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|---|---|
| 62 | 30 cps to over 150 Mc |
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| MODEL | FREQUENCY RANGE |
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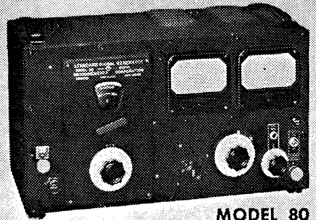
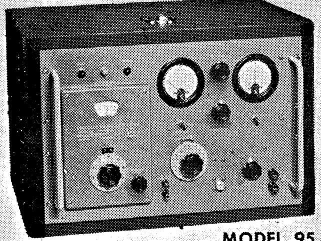
| 59 | 2.2 Mc to 420 Mc |
| 59 UHF | 420 Mc to 940 Mc |

## CRYSTAL CALIBRATORS

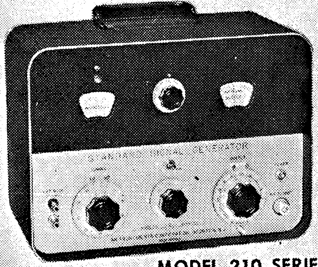
| MODEL | FREQUENCY RANGE |
|---|---|
| 111 | 250 Kc to 1000 Mc |
| 111-B | 100 Kc to 1000 Mc |



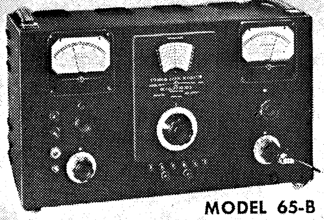
MODEL 80
STANDARD SIGNAL GENERATOR



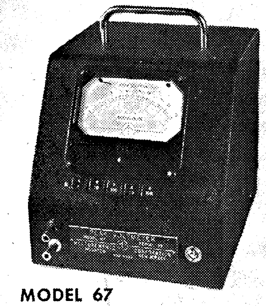
MODEL 95
FM STANDARD SIGNAL GENERATOR



MODEL 210 SERIES
FM STANDARD SIGNAL GENERATOR



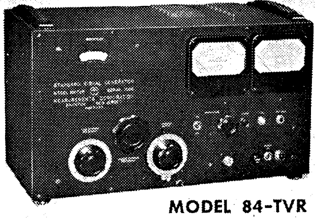
MODEL 65-B
STANDARD SIGNAL GENERATOR



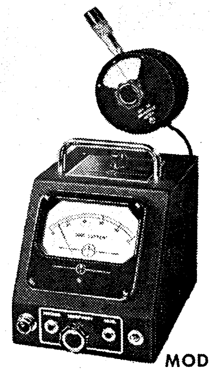
MODEL 67
PEAK-TO-PEAK VOLTMETER

MODEL 71
SQUARE WAVE GENERATOR

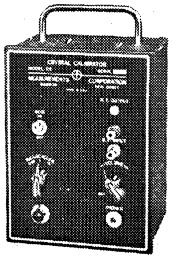
MODEL 72
SQUARE WAVE GENERATOR



MODEL 84-TVR
STANDARD SIGNAL GENERATOR



MODEL 59
MEGACYCLE "GRID-DIP" METER



MODEL 111
CRYSTAL CALIBRATOR

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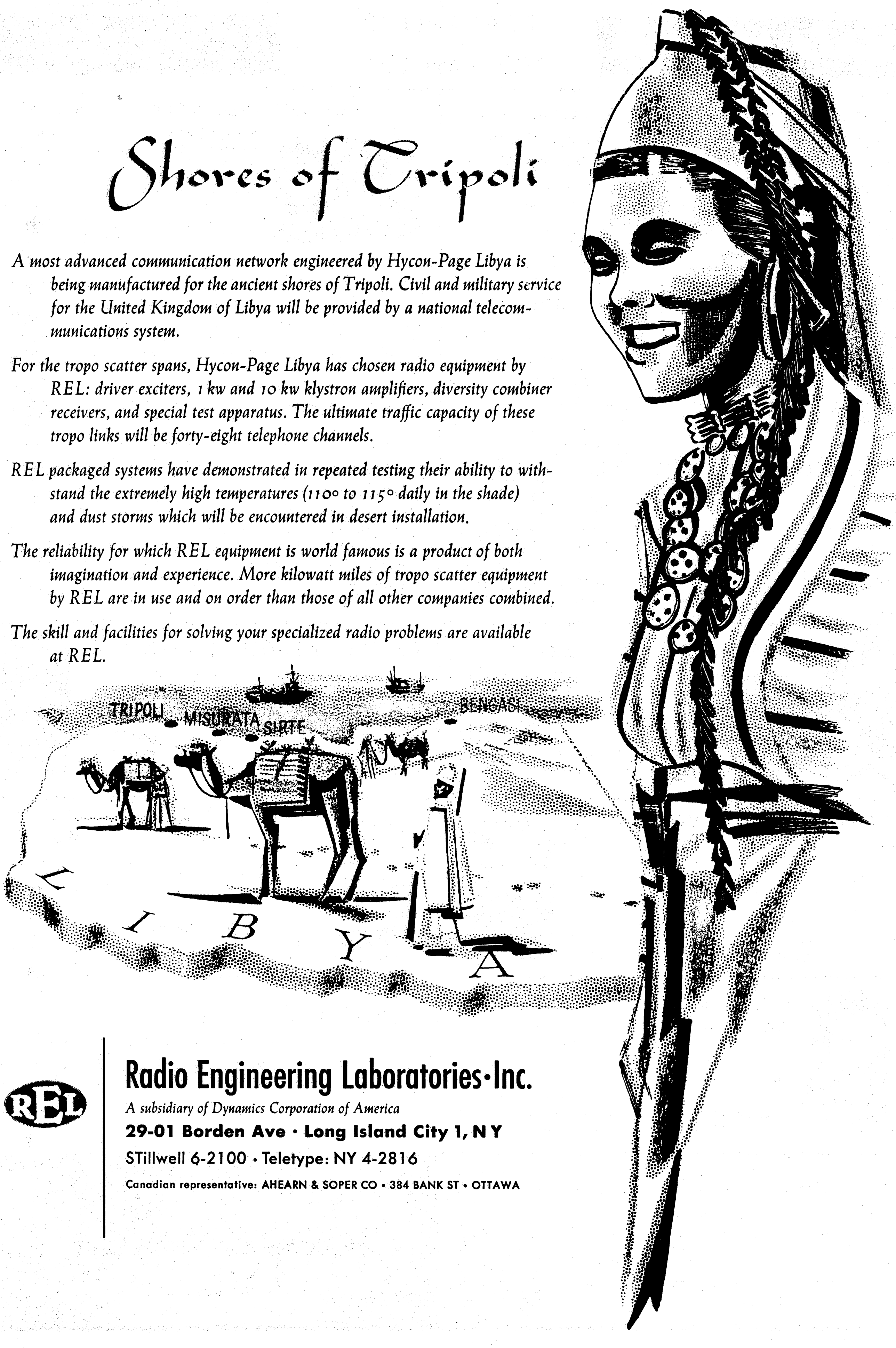

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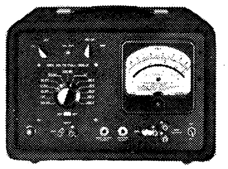

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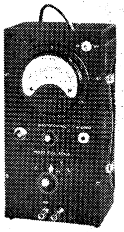
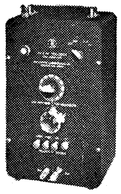
| Frequency Range | 5 cps — 500 kc |
| Accuracy | 3% 15 cps — 150 kc<br>5% elsewhere |
| Stability of Internal Calibrator | 0.5% |
| Input Impedance . . . | 10 megs shunted by 18 µµf below 10 mv<br>10 megs shunted by 8 µµf above 10 mv |

## AUDIO to 150 kc MODEL 300



| | |
|---|---|
| Voltage Range | 1 mv — 100 v |
| Frequency Range | 10 cps — 150 kc |
| Accuracy | 2% ENTIRE RANGE |
| Input Impedance | ½ meg shunted by 30 µµf |

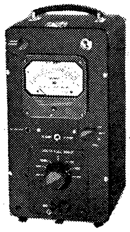
## DC & AC PRECISION CALIBRATOR MODEL 420



| | |
|---|---|
| Voltage Range | 0-10 v RMS; Pk-to-Pk; or DC |
| Frequency (Std. Model) | 1 kc<br>(other values on special order) |
| Accuracy (long term) | Better than 0.5% above 1 mv |
| Distortion and Hum | Less than 0.25% |
| Setting Resolution | Approaches 0.01% above 10 mv |
| Output Impedance (AC) | 2-20 ohms depending on range setting |

## SUB-AUDIO to 150 kc MODEL 302C

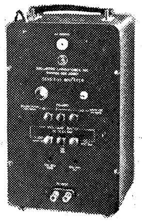
Battery Operated



| | |
|---|---|
| Voltage Range | 100 µv — 1000 v |
| Frequency Range | 2 cps — 150 kc |
| Accuracy | 3% 5 cps — 100 Kc<br>5% elsewhere |
| Input Impedance | 2 meg shunted by 10 µµf* |

*Shunt capacitance, 25 µµf on two most sensitive ranges

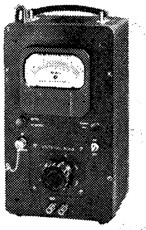
## SENSITIVE INVERTER MODEL 700



For Measuring DC Voltages when combined with any AC Voltmeter

| | |
|---|---|
| Voltage Range | 1 µv — 100 v DC |
| Ratios DC Input to RMS Output | 1:100 & 10:1 |
| Accuracy | 1% 100 µv — 100 v |
| Input Resistance | >10 meg for 1:100<br>50 meg for 10:1 |

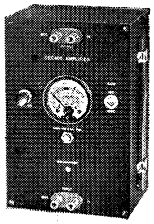
## PEAK-to-PEAK MODEL 305



| | |
|---|---|
| Voltage Range | 1 mv — 1000 v pk-to-pk |
| Frequency Range | 10 cps — 100 kc (sine wave) |
| Pulse Width | 3 µsec — 250 µsec |
| Min Rep Rate | 20 pulses per sec |
| Accuracy | 5% for pulses |
| Input Impedance | 2 meg shunted by 8 µµf* |

*Shunt capacitance, 15 µµf on two most sensitive ranges

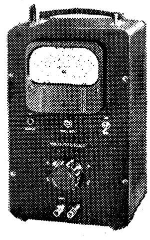
## DECADE AMPLIFIER MODEL 220B



For Increasing the Sensitivity of any AC Voltmeter by 10 or 100 times

| | |
|---|---|
| Voltage Range | 20 µv — 50 mv |
| Frequency Range | 10 cps — 150 kc |
| Accuracy | 2% ENTIRE RANGE |
| Input Impedance | 5 meg shunted by 15 µµf |

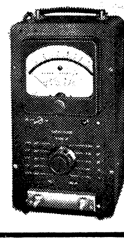
## AUDIO to 2 mc MODEL 310A



| | |
|---|---|
| Voltage Range | 100 µv — 100 v<br>Down to 40 µv at reduced accuracy |
| Frequency Range | 10 cps — 2 mc<br>As null detector 5 cps. — 4 mc |
| Accuracy | 3% 15 cps — 1 mc<br>5% elsewhere |
| Input Impedance | 2 meg shunted by 9 µµf* |

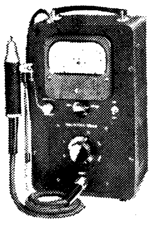
*Shunt capacitance, 19 µµf on two most sensitive ranges

## DIRECT READING CAPACITANCE METER MODEL 520



| | |
|---|---|
| Capacitance Range | 0.01 µµf to 12 µf<br>in 9 decade ranges covering over a billion to 1 |
| Accuracy | 2% above 0.1 µµf<br>5% below 0.1 µµf |
| Capacitor Power Factor | 0.15 |
| Test Frequency | 1 kc |

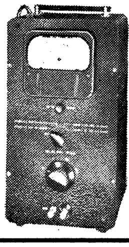
## AUDIO to 6 mc MODEL 314



| | |
|---|---|
| Voltage Range | 1 mv — 1000 v<br>(100 µv — 1 mv without probe) |
| Frequency Range | 15 cps — 6 mc |
| Accuracy | 3% 15 cps — 3 mc<br>5% elsewhere |
| Input Impedance | 11 meg shunted by 8 µµf<br>(1 meg shunted by 25 µµf without probe) |

**ACCESSORIES** are available for all voltmeters to extend voltage measurements down to 20 µv and up to 10 kv, and to measure currents from 0.1 µamp to 10 amp, and to provide DC from the Model 300 Voltmeter to drive external recorders or remotely located meters.

## INFRASONIC to 30 kc MODEL 316



| | |
|---|---|
| Voltage Range | 20 mv — 200 v pk-to-pk |
| Frequency Range | 0.05 cps — 30 kc<br>(Down to 0.1 cps with correction) |
| Accuracy | 3% ENTIRE RANGE |
| Input Impedance | 10 meg shunted by 17 µµf<br>or 40 µµf depending on setting |

**BALLANTINE LABORATORIES, Inc.**

**Boonton, New Jersey**