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Microwave Generators for the I. E. N. Caesium Standard

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Summary. — The paper describes two microwave generators employed at the I.E.N. to excite a resonance of the hyperfine structure of the caesium atom, at a frequency of approximately 9192 Mc/s, with the molecular beam technique. Methods for measuring the phase drift and frequency stability of the source are considered.

1. Introduction

The construction of an Atomic Frequency Standard has been initiated at the Istituto Elettrotecnico Nazionale "Galileo Ferraris" (I.E.N.) in Turin [1][1]). A resonance of the hyperfine structure of the caesium atom is used. The instrument works as a spectroscope with high resolving power.

A beam of caesium atoms evaporate from an oven having a constant temperature of 200 °C, charged with caesium chloride and sodium. The beam is contained in a stainless steel tube evacuated to a pressure of some units in 10^{-7} mm of Hg. Parts of the atoms, by a couple of non-uniform magnetic fields are obliged to follow particular paths and to focus a detector, after being selected by a slit.

The detector consists of a tungsten wire having a temperature of about 1000 °C surrounded by a cylindrical negative plate which collects the atoms thermally ionized by the wire. The plate is connected to an electrometer of high sensitivity whose indication depends upon the intensity of the selected beam. Only the atoms having a suitable combination of initial directions, velocities, and magnetic moment, are selected by the slit and strike the detector wire. Between the two magnets the beam is submitted to a high frequency magnetic field which produces the transition between the two states designed by the quantum number F, $m_F(4,0)$ and F, $m_F(3,0)$ [2]. All the atoms which have undergone the transition cannot reach the detector because their magnetic moment has changed. Thus the electrometer dip indicates that the high frequency field is tuned on the resonance of the caesium atom, i.e. about 9192 Mc/s. A uniform magnetic field of about 4 A turns/m is superimposed to separating the field dependent Zeeman resonant lines from the central line $m_F = 0$, which is almost independent of the field.

Because of the very high resolving power of the instrument [3] it is necessary to have a high degree of stability and frequency purity of the radio-frequency source.

This paper describes the microwave generators which have been constructed for this purpose.

Two different types of generators have been made. One of them consists of a klystron stabilized by a high Q cavity through a Pound circuit. The other is a quartz oscillator with a chain of frequency multipliers. The second will be employed for routine measurements, the first, which has a wide tuning range and is able to supply more power, will be used for measurements on the microwave circuits, and to explore the whole pattern of resonances due to the *Zeeman* effect.

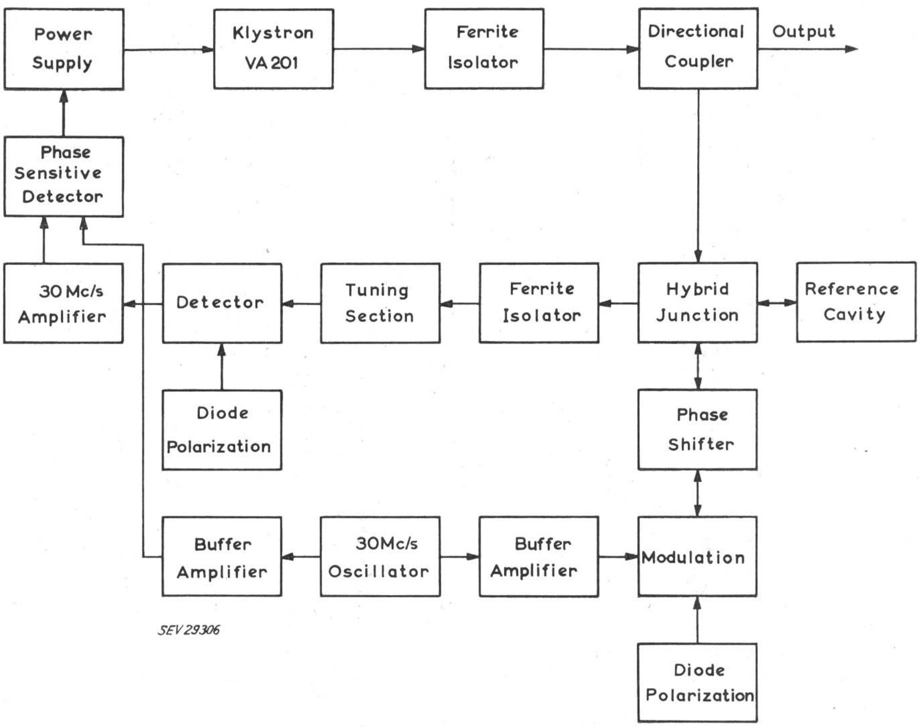

Fig. 1
Block diagram of klystron generator with Pound stabilization

2. Klystron Generator with Pound Stabilization

The Pound circuit is shown in the block diagram of Fig. 1. A klystron (type Varian V A 201) is used with a cylindrical cavity resonator oscillating with the mode TE_{019} at the frequency of about 9192 Mc/s. The loaded Q is nearly $4 \cdot 10^4$ and the tuning range is 10 Mc/s. The description of the stabilizing circuit operation is omitted here because it is well known in the literature [4; 5]. However some modifications have been introduced in order to improve the circuit performance. Small mismatches in the detector mount can produce reflected waves mainly at carrier frequency, these waves returning to the hybrid circuit. Half of the power output reaches the modulator where side bands are produced. These return to the detector and by mixing with the carrier can produce undesirable signals which overload the intermediate frequency amplifier.

To minimize this, a ferrite isolator was used between the detector and the hybrid circuit. A second ferrite isolator

[1]) Refer to the Bibliography at the end of the article.

was used at the output of the klystron. Pulling effects due to the load are in addition reduced by means of a 10 db directional coupler.

These improvements simplify the manipulations of the microwave circuit controls required to obtain the required frequency stability.

Stabilized power supplies giving a very high degree of stabilization [6] are used for the d.c. filament supply of the klystron and of the tubes of the stabilizing circuit. The anode power supplies have a stability of 1‰ and a residual hum of 10 μV [7]. Screened coaxial cables have been used for all connections.

In the prototype unit the reference cavity was made of steel with the inner surfaces plated with copper. A second cavity made of invar, now in construction, will be vacuum sealed and maintained at a constant temperature of 0.01 °C in a thermostat. Preliminary measurements have been carried out, only with the steel cavity, in order to verify the frequency changes produced by variations of some parameters in the Pound circuit.

3. Circuit Parameters affecting Frequency Stability

The 6.3 Mc/s quartz oscillator and the chain of frequency multipliers, which will be described later, have been used in the circuit shown in Fig. 2. By means of a 10 db directional coupler and a mixer, the klystron output is mixed with the signal supplied by the frequency multipliers, and the beat note is observed with an oscilloscope.

A signal at a frequency of about 170.2 Mc/s derived from the chain of multipliers is mixed with a harmonic of the primary standard at 100 kc/s and the beat frequency is measured with an electronic counter.

The measurement of the frequency shift due to variations in circuit parameters is made in the following manner. The frequency of the 6.3 Mc/s oscillator is checked with the counter. A 1 kc/s signal, supplied by a stable audio frequency generator calibrated with the counter, is applied to the X-axis of the oscilloscope and the output of the mixer to the Y-axis. The reference cavity is tuned until an ellipse is obtained on the screen of the oscilloscope. Then the klystron frequency and the harmonic of the 6.3 Mc/s crystal differ by 1 kc/s. The parameter variation is effected and the audio frequency oscillator is tuned until the ellipse reappears on the screen, the tuning difference corresponding to the frequency shift. As the frequency stability of the reference cavity without thermostat was poor, the measurement was carried out within 1 second. Moreover, the measurements were made after a warm-up period of 24 hours and at a time when the room temperature variation had an inversion.

Several measurements of the frequency shift versus parameter variations have been made. The measurements were carried out with cyclic parameter variations. Diagrams indicating the disturbing effect of the cavity instability were eliminated.

The following data have been obtained:

Modulator diode biasing current	70 c/s per mA
Detector diode biasing current	210 c/s per mA
Waveguide phase-shifter	770 c/s per degree
Klystron temperature coefficient	not measurable.

The klystron VA-201 was utilized in the 5¾ mode. The loop gain was about 10^4, the same being the value of the stabilization factor, with a -6 db bandwidth of 200 c/s.

The lowest frequency obtained in the beat was about 20 c/s. This limit is imposed by the temperature coefficient of the steel cavity (100 kc/s per °C) and the temperature fluctuations of the room.

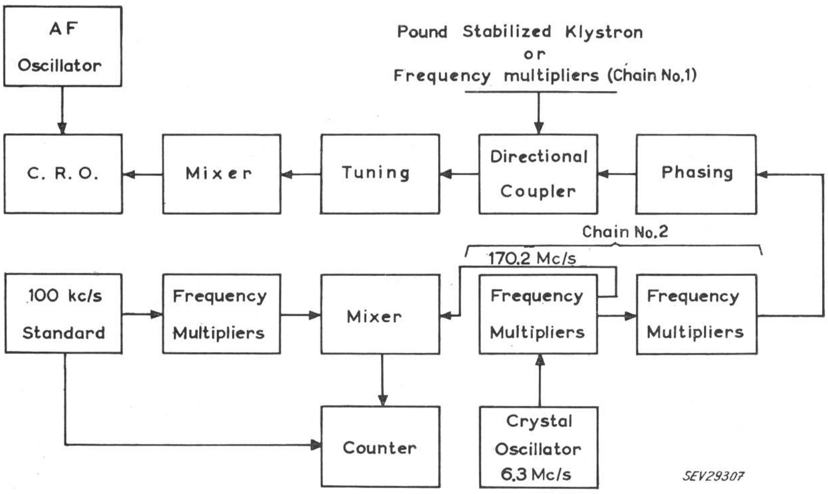

Fig. 2
Phase and frequency stability measurement set up

4. Crystal Oscillator and Frequency Multipliers

For routine measurements with the caesium molecular beam, in order to calibrate the quartz clocks, a second microwave generator was constructed. It consists of a quartz crystal at about 6.3 Mc/s and a chain of frequency multipliers.

The possibility of utilizing directly the 100 kc/s primary standard was not considered because it would have been necessary to use a frequency synthesizer to obtain the same frequency of the caesium line, and this probably would have introduced a significant phase modulation [8].

The block diagram of the unit is shown in Fig. 3. The circuit of the 6.3 Mc/s oscillator will be described in a paper to be published later. The output of this oscillator feeds a chain of four triplers, of conventional design with tubes QQE 03/12 and QQE 03/20. The 510.7 Mc/s output feeds the tripler EC 55 mounted with $\lambda/4$ coaxial lines. The power output of the tube is 0.4 W, which is sufficient to drive a second EC 55 as a doubler with an output of 90 mW at a frequency of 3064.2 Mc/s. A Varactor MA 460D, used as a third-harmonic generator, gives a power of 11 mW at 9192.6 Mc/s.

The input and output coaxial lines are tuned to $3\lambda/4$. As the loaded Q of the input coaxial cavity is low, it was possible to use fixed tuning. Input and output couplings are of the capacitive type and are variable for impedance matching. The anode cavity has a tuning range of about 20 Mc/s. The mounting design was such as to avoid any mechanical stress in the tube.

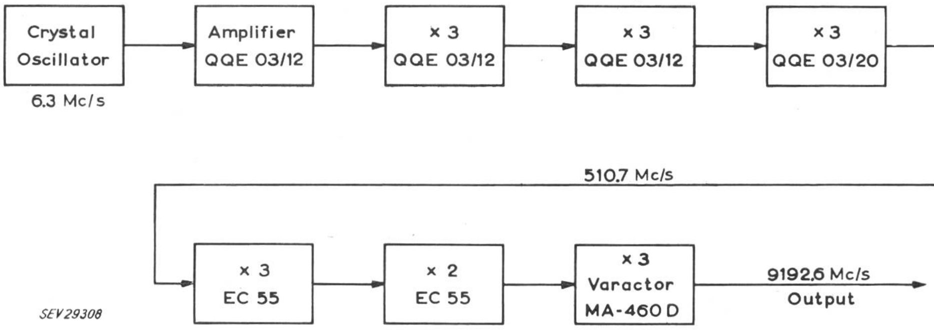

Fig. 3

Block diagram of the frequency multipliers

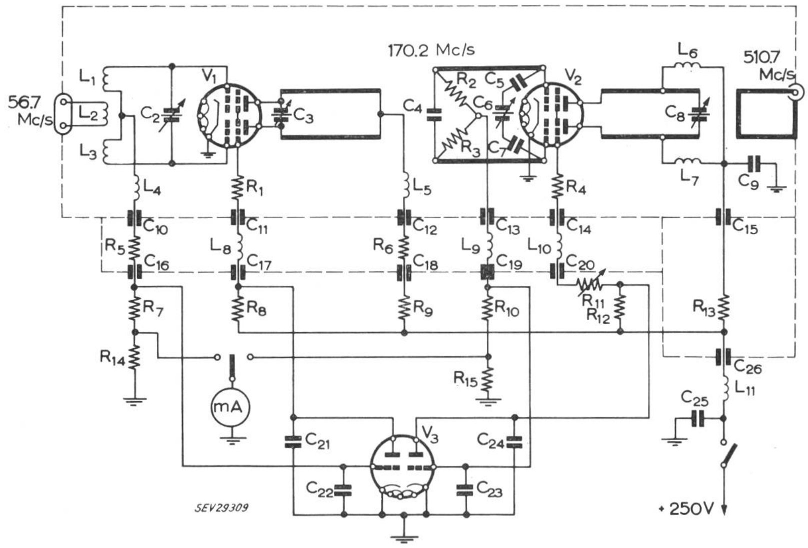

Fig. 4

Tripler circuits of the panel 56.7 Mc/s to 510.7 Mc/s

V1, V2 QQE 03/20; *V3* E 182 CC; $L_4...L_{11}$ R-F choke coils

The design was made with great care in order to reduce phase modulation due to mechanical vibrations and sound waves. Power supplies with a high degree of stabilization [6; 7] have been used. The circuit of the panel 56.7 Mc/s to 510.7 Mc/s is shown in Fig. 4. A cross-sectional drawing of the doubler 1532.1 Mc/s to 3064.2 Mc/s is shown in Fig. 5.

The last tripler consists of a non-linear capacity harmonic generator. The insertion loss, tripling from 3064.2 Mc/s, was only 9 db. With silicon and germanium diodes the insertion loss was about 20 db, changing considerably from one diode to the other. A cross-sectional drawing of the harmonic generator is shown in Fig. 6. Optimum power

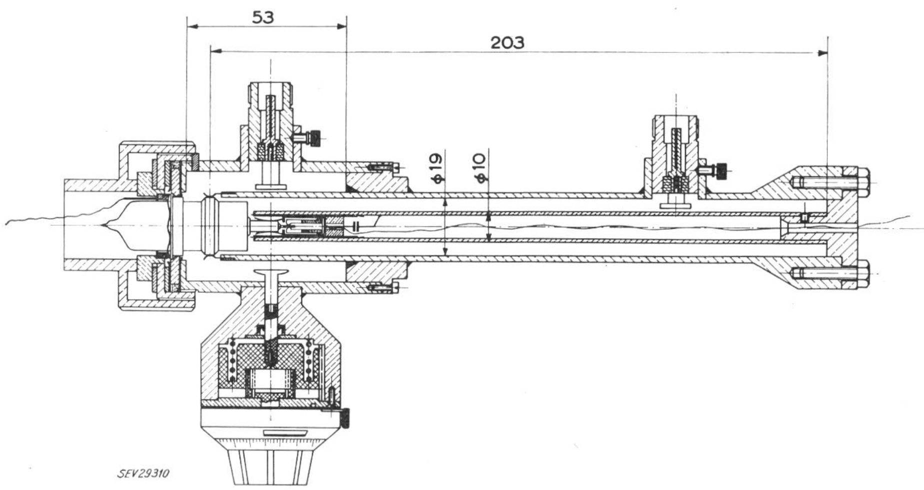

Fig. 5

Doubler 1532.1 Mc/s to 3064.2 Mc/s

output was obtained with a reverse bias somewhat less than 6 V.

5. Phase Stability

Measurements of phase stability of the frequency multipliers were carried out.

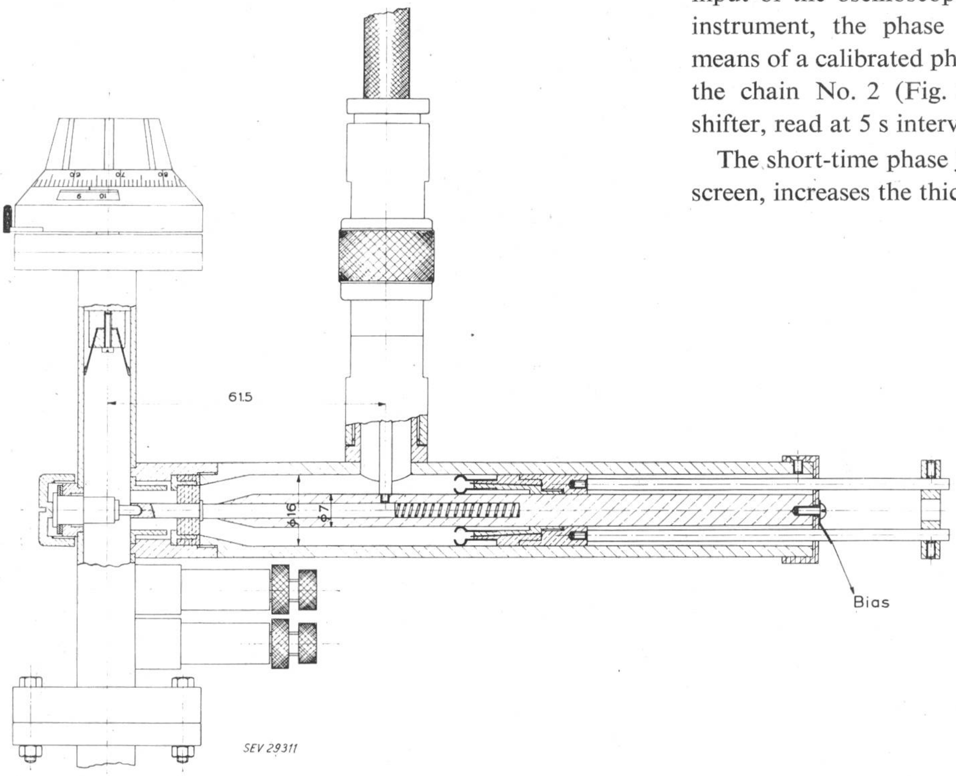

Fig. 6
Harmonic generator 3064.2 Mc/s to 9192.6 Mc/s

With reference to the block diagram of Fig. 2, the measurement was made by observing with an oscilloscope the beat between the multiplier chains No. 1 and No. 2, both being fed by the 6.3 Mc/s quartz oscillator. The audio frequency oscillator, indicated in the figure, is not used for this measurement because the beat signals have the same frequency. The directional coupler has a coupling factor of 3 db.

Long-time phase drift as well as short-time phase jitter were observed. As a consequence there is a limitation to the accuracy of the frequency comparison. The long-time phase drift was measured in the following way. A millivoltmeter, with a time constant of 1 s, was connected parallel to the input of the oscilloscope. Observing the indication of the instrument, the phase variations were compensated by means of a calibrated phase shifter inserted at the output of the chain No. 2 (Fig. 2). The indications of the phase shifter, read at 5 s intervals, are recorded in Fig. 7.

The short-time phase jitter, observed on the oscilloscope screen, increases the thickness of the trace which is a maximum when the beating signals are at 90° out of phase. This condition was maintained during the measurement. The maximum slope of the diagram of Fig. 7 gives a phase shift of about 430° over a period of 1 minute. This corresponds to a maximum frequency variation of about 2 parts in 10^{12} at a frequency of 10 000 Mc/s.

The amplitude of the noise which increases the trace thickness on the oscilloscope was about 5 % of the amplitude

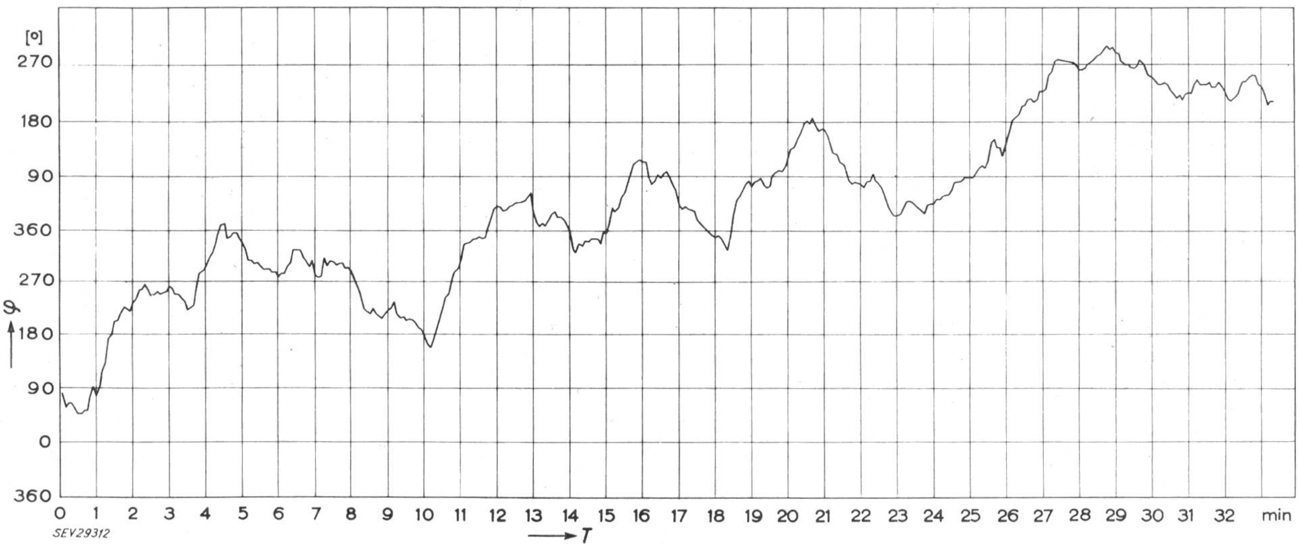

Fig. 7
Phase variations of the multiplier chain
φ Phase; T time

of the beat. Owing to a lack in the definitions as far as the author knows, it is impossible with this measurement to obtain a figure of the accuracy of the frequency comparison. To avoid this difficulty, measurements of short-time frequency stability have been carried out.

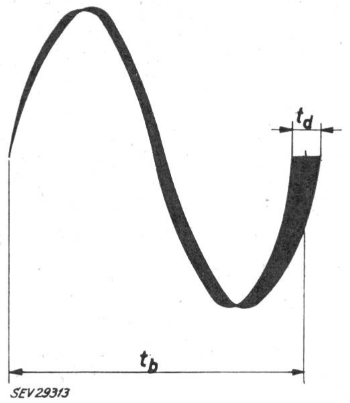

Fig. 8

Waveform showing the spreading at the end of one cycle beat note

t_b Beat cycle time; t_d Spead after one cycle

The outputs of the multiplier chains, fed by two different 6.3 Mc/s quartz oscillators, were mixed by means of the circuit shown in Fig. 2. Adjusting the frequency of one of the oscillators, a beat of 100 c/s was obtained. One cycle of the beat note was observed on the oscilloscope. The beginning of the cycle was synchronized, but the end showed some spreading (Fig. 8). The short-time frequency stability can be calculated from the following relation:

$$f_d = f_b \frac{t_d}{t_b}$$

where:

f_d peak-to-peak frequency deviation

$f_b = \frac{1}{t_b}$ beat frequency

t_d spread after one cycle.

This measurement is correct if f_b is at least ten times higher than the frequency deviation or the rate of the frequency deviation. However, f_b should not be too high, as otherwise an accurate measurement of t_d cannot be made. The peak-to-peak frequency deviation measured was 10 c/s. This figure includes the stability of the quartz oscillator, and it was observed that the second oscillator was not so good as the first one.

6. Frequency Resolution

The caesium beam will be used as a passive resonator in order to calibrate at regular time intervals the quartz primary standards. To carry out the measurement, the frequency of the 6.3 Mc/s crystal oscillator is slowly varied in order to tune on the caesium resonance. At the same time the oscillator is continuously calibrated by the primary standard. Therefore the frequency resolution will depend essentially upon the short-time frequency stability of the microwave source. This instability gives a limitation in the accuracy of the measurement because it reduces the resolving power by flattening the resonance dip of the beam detector output.

One of the factors which must be considered in order to improve the short-time frequency stability, is the signal-to-noise voltage ratio of the 6.3 Mc/s quartz oscillator. In the case of the circuit of Fig. 2, using a wide-band oscilloscope zero-beat indicator and assuming an oscillator noise with a Gaussian probability density, the signal-to-noise voltage ratio of the oscillator must be greater than 100 db to obtain a frequency uncertainty of some parts in 10^{10} [9]. Hence the design of the quartz-stabilized oscillator was made with this figure in mind.

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