

Lev Termen's Great Seal Bug Analyzed

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INTRODUCTION

To take the heat off Soviet accusations of American aggression following the downing of Gary Powers's U-2 spy plane, on May 26, 1960, U.S. Ambassador Henry Cabot Lodge, Jr., displayed a large carved relief of the Great Seal of the United States at a United Nations' Security Council debate. Unusually, the seal contained a small cavity into which had been inserted a novel radio transmitter that had been used to bug the ambassador's residence in Moscow.

On August 4, 1945, this seal, shown in Figure 1, had been presented to W. Averell Harriman, the U.S. ambassador to the Soviet Union, by the Soviet Young Pioneers (the equivalent of the Boy Scouts) as a gesture of friendship [1], [2]. After passing a routine x-ray check, the seal had been hung behind Harriman's desk in his office at Spaso House, No. 10 Spasopeskovskaya Square, Moscow (the official residence of U.S. ambassadors to the Soviet Union from 1934).

This article examines the anecdotal and technical evidence relating to the bug in an attempt to determine whether it was just an early example of a passive radio-frequency identification (RFID) tag or a more sophisticated device that relied on harmonic reradiation. These considerations are important, because they resulted in the bug's remained undetected until it was found, rather fortuitously, during George F. Kennan's ambassadorship in September 1952. Most bug sweeps were undertaken by technicians after hours, but according to Kennan [3], he had been asked by one of the security technical officers, Joseph Bezjian, if he could spend an evening going through the motions of performing some official work. It was during this session, while dictating to his secretary, that the bug was activated by the Soviet eavesdroppers. Its broadcasts had been de-

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Figure 1.
Copy of the Great Seal of the United States presented to W. Averell Harriman [2].

tected using a wideband (untuned) crystal detector [4], or according to Wright [5], the device had been discovered using a tunable receiver operating in the "howl-round" mode around 1800 MHz. The howl-round principle operates by generating an amplified audio signal based on the demodulated radio-frequency signal transmitted by a bug. This feedback process produces a high-pitched squeal that can be useful in pinpointing the position of the transmission.

After some searching, a small cylinder, about 20 mm in diameter, attached to a short rod antenna was found within the seal. The cylinder appeared to be some sort of microphone, as one face was covered by a thin diaphragm. Tiny holes drilled beneath the eagle's beak (or through its nostril) coupled sound from the room to the device [4].

The bug had apparently been developed by Lev Termen (later Leon Theremin) during his time at the Sharashka (secret research and development labs associated with the Soviet Gulag labor camp system) at Kuchino, which was a facility for radio electronics and measuring devices near Moscow.



Termen was both a musician and a physicist and is probably best known as the inventor and player of the aetherphone, later known as the thereminvox, which had so impressed Lenin. After World War I, he had been invited to head a new experimental laboratory in the Ioffe Physical Laboratory, where he worked on high-frequency measurement methods. In 1927, during an international tour to promote his inventions, he decided to stay in the United States, where he changed his name to Leon Theremin. He returned, abruptly and for unknown reasons, to the Soviet Union in 1938; shortly after, he was arrested during one of Stalin's purges and sentenced to 8 years in the Kolyma Gulag. Here he would almost certainly have died, but fortunately after only a few months, he was transferred to the Sharashka to work on military projects [6].

PHYSICAL CHARACTERISTICS OF THE BUG

According to various descriptions and drawings of the bug [1], [2], it consists of a silver-plated copper cylinder about

13 mm long and 20 mm in diameter, as shown in Figure 2. A central tuning post "mushroom" attached to a threaded backplate can be positioned relative to the thin conductive diaphragm covering the front of the cavity to adjust the capacitance and hence the its resonant characteristics. Finally, an insulated rod antenna extending through the side of the cylinder terminates in a coupling disc within the cylinder.

Some sources include slots cut through the walls of the cylinder to limit the air-cushioning effects, but these have not been reproduced in the figure, nor are they considered during the subsequent analysis.

PRELIMINARY ANALYSIS

According to one reference [1], the bug is simply a long-range passive RFID tag that uses standard modulated backscatter principles. However, other references suggest that it was tuned to one of the harmonics of the illuminating frequency [2], [5], [7]. This could be the reason howl-round techniques, standard at the time, were not effective unless

the bug was being illuminated by the external microwave source at the same time.

If the external antenna is considered as both the receiver for the excitation signal and the transmitter, it should be resonant at those frequencies. Taking into account the end effect for a $\lambda/4$ Marconi antenna with a length-to-diameter ratio of 50:1, the scale factor should be $K = 0.955$ [8]. An antenna with $L = 0.228$ m (9 in.) would therefore be resonant at

$$f_{res} = \frac{Kc}{4L}. \quad (1)$$

This equates to a resonant frequency of $f_{res} = 314$ MHz in air. For higher-frequency operation, the resonant frequencies are not direct multiples of this fundamental because the end effect only occurs

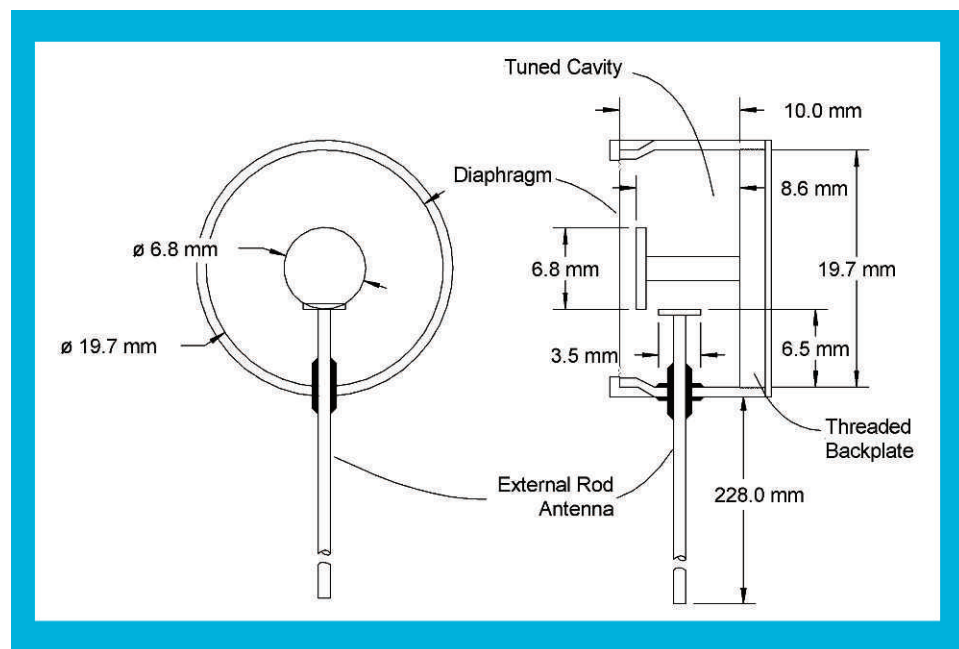


Figure 2. Drawing showing the construction of the bug found in the great American seal.

Table 1.

Resonant Frequencies for a 0.228-m Marconi Antenna	
Number of Quarter Wavelengths	Resonant Frequency (MHz)
1	314
2	524
3	972
4	1301
5	1630
6	1959

once. The general formula for the resonant frequency, where N is the number of quarter wavelengths, is [8]

$$f_{res} = \frac{c(N - 0.045)}{4L}. \quad (2)$$

Table 1 lists the first six resonant frequencies, from which it is clear that the 1800-MHz howl-round frequency mentioned by Wright [5] is feasible. The frequency of the illuminating source would still be reasonably well matched to the antenna if the 1800-MHz signal was a harmonic of the fundamental, say, 600 or 900 MHz.

The main question that now needs to be answered is, Would the cavity resonate at one of these frequencies?

DETAILED ANALYSIS

CAVITY RESONANCE FREQUENCY

According to [1], [2], and [4], the bug was made from silver-plated copper. However, to simplify the modeling process using the high-frequency structure simulator (HFSS), the

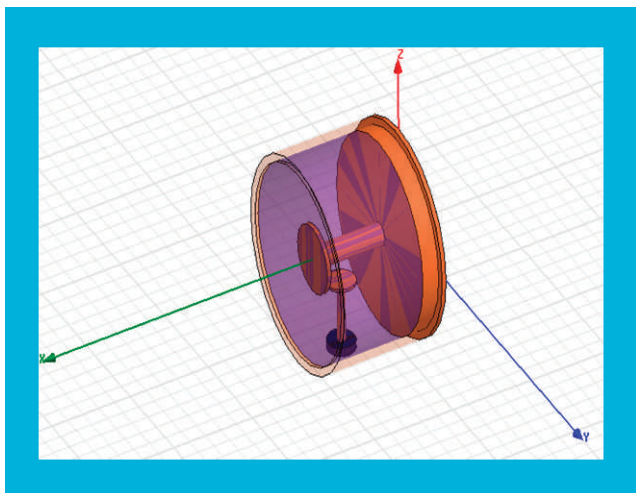


Figure 3.
HFSS-generated model of the cylindrical portion of the bug.

Table 2.

Eigenmode Resonant Frequencies for the Cavity		
Eigenmode	Frequency (GHz)	Q
1	1.816+j0.000475	1911
2	6.558+j0.001475	2225
3	15.774+j0.00144	5475
4	16.489+j0.00169	4888
5	16.986+j0.00159	5340
6	18.172+j0.00160	5670

cylinder material was specified to be copper, with polytetrafluoroethylene insulating the antenna feed, as shown in Figure 3. The resonant characteristics of the cavity were then determined using eigenmode analysis.

Examination of the first four modes, listed in Table 2 and shown in Figure 4, indicates that most of the resonant frequencies are too high. However, the first mode is sufficiently close to 1800 MHz to be useful. In addition, it can be seen that this mode couples strongly to the diaphragm and so should be sensitive to acoustically induced vibrations.

ACOUSTIC COUPLING

A sensitivity analysis made for the tuning post and backplate position, as a function of the resonant frequency of Mode 1, is shown in Figure 5. For a linear fit, the slope of the graph is $-2.82 \text{ MHz}/\mu\text{m}$.

As can be seen from Figure 6, acoustically induced displacements of the diaphragm result in changes of the resonant frequency of the cavity with respect to the illumination frequency (and its harmonics). This in turn results in changes in the amplitude of the reradiated signal in a manner similar to that generated by an old-fashioned frequency-modulation discriminator. Depending on the Q of the cavity, and the offset between its resonant frequency and the harmonic, a reasonably undistorted amplitude modulation (AM) signal is produced.

DISPLACEMENT OF THE DIAPHRAGM

All of the references to the bug talk of an extremely delicate, gossamer-thin diaphragm that is easily damaged, so it can be assumed that the diaphragm was sufficiently thin and that its displacement would equal the acoustically induced displacement of the air molecules during normal conversation within the ambassador's office.

The peak displacement of air molecules y_m (in meters) is related to the peak acoustic pressure p_m (in pascals) according to [9], by

$$y_p = \frac{p_m}{k\rho_0 v^2}, \quad (3)$$

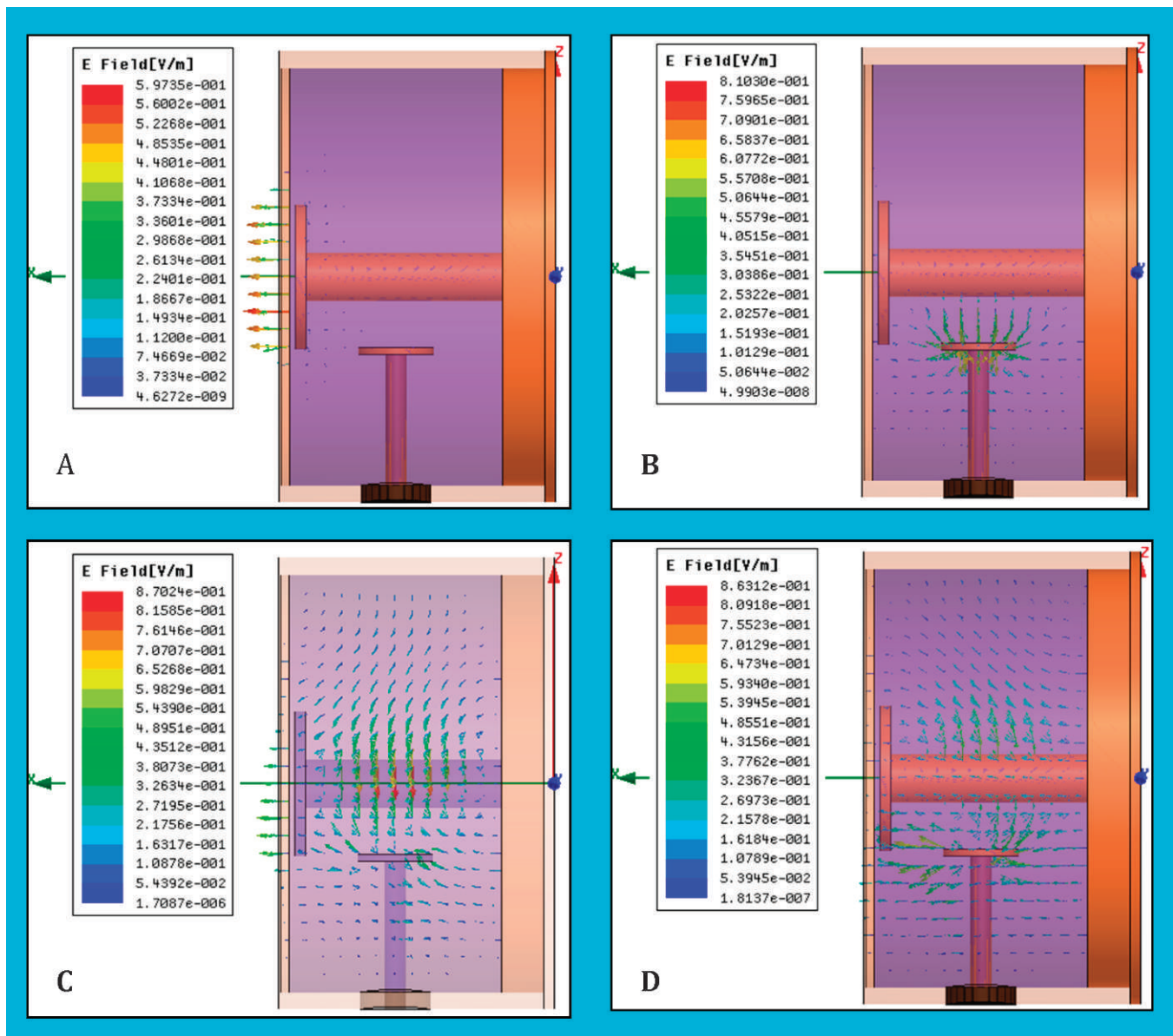


Figure 4. Electric fields within the cavity related to the first four eigenmodes: (a) Mode 1, (b) Mode 2, (c) Mode 3, and (d) Mode 4.

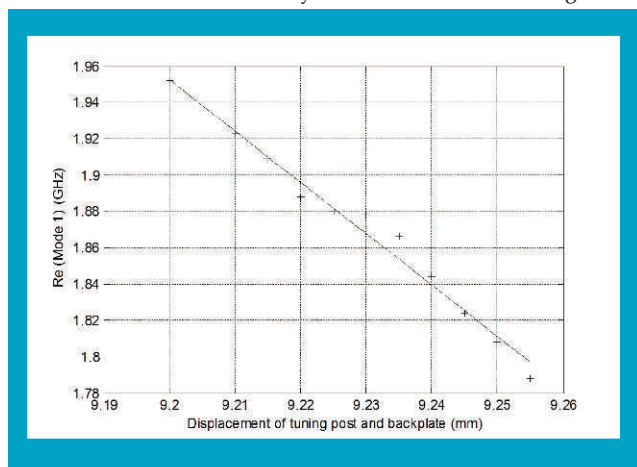


Figure 5. Sensitivity analysis of Mode 1 as a function of backplate position.

where $k = 2\pi/\lambda_m$ is the wave number, ρ_o (in kilograms per cubic meter) is the air density, and v (in meters per second) is the velocity of sound in air.

The sound pressure level (SPL) for normal conversation is about 60 dB at a frequency around 1000 Hz. This equates to a peak acoustic pressure p_m of 0.028 Pa. The peak air (and hence diaphragm) displacement is about 10 nm for $v = 340$ m/s, $\rho_o = 1.204$ kg/m³, and $\lambda_m = 0.34$ m.

Using the results presented in Figure 5, this displacement results in a shift in the resonant frequency of ± 30 kHz between the peak positive and the peak negative displacements. For quiet conversation, the SPL is reduced, with a typical SPL = 45 dB, which equates to a shift in resonant frequency of only ± 5.5 kHz.

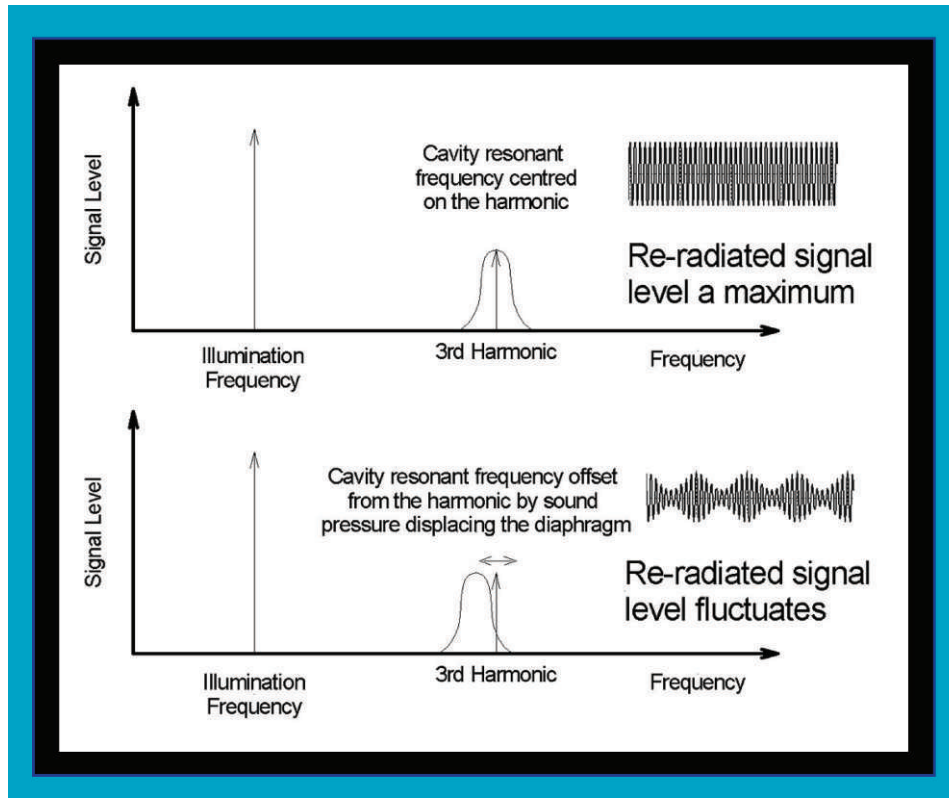


Figure 6.
Conversion of acoustic signals into an amplitude-modulated carrier.

The relationship between the Q and the bandwidth, β (in hertz), of a tuned circuit is [10]

$$Q = \frac{f_{res}}{\beta}. \quad (4)$$

Therefore, for a calculated $Q = 1911$ at a resonant frequency of 1800 MHz, the half-power bandwidth is $\beta = 0.94$ MHz. This is much larger than the acoustically induced changes in the resonant frequency; therefore, little AM would occur unless the illumination frequency harmonic was tuned off resonance, as shown in Figure 6.

AMPLITUDE MODULATION

The AM of a carrier (in this case, the harmonic) with a frequency f_{res} (in hertz), by a sinusoidal signal with a frequency f_m (in hertz) can be described by [11]

$$v_{am}(t) = [1 + A_{am} \cos 2\pi f_m t] \cos 2\pi f_{res} t. \quad (5)$$

The percentage modulation ($A_{am} \times 100$) for the signal is determined by the offset of the harmonic from the resonant frequency and shift in the resonant frequency with acoustic input, as illustrated in Figure 7. In this case, the harmonic is centered on 1800.5 MHz, and the total shift in the resonant frequency is ± 30 kHz on either side of 1800 MHz. It can be

seen that a change in amplitude of 0.6 dB occurs. This equates in a change in output voltage after detection by a factor of only 1.07 (a percentage modulation of 7%).

Such a small modulation depth is obviously not ideal, but it would still have been easy to detect using a standard narrow-band heterodyne receiver followed by one of several vacuum-tube AM detector configurations used at the time [12].

HARMONIC GENERATION

If the bug operated in a similar manner to a modern RFID tag, by modulating the backscatter amplitude, the power of the modulated component compared to that reflected from other objects within the illuminating beam would be extremely small and hence difficult to detect. This option is analyzed later in this article.

The question that now needs to be answered is, How could the tag generate harmonics of the illumination frequency?

It is well known that passive parts of antennas and closely located objects can support nonlinear current-voltage relationships and thus support the generation of harmonics. According to Golikov et al. [13], there are two dominant generators of nonlinearities, namely, contact generators, of which loose, oxidized or contaminated metallic joints are examples, and material generators, such as ferromagnetic ma-

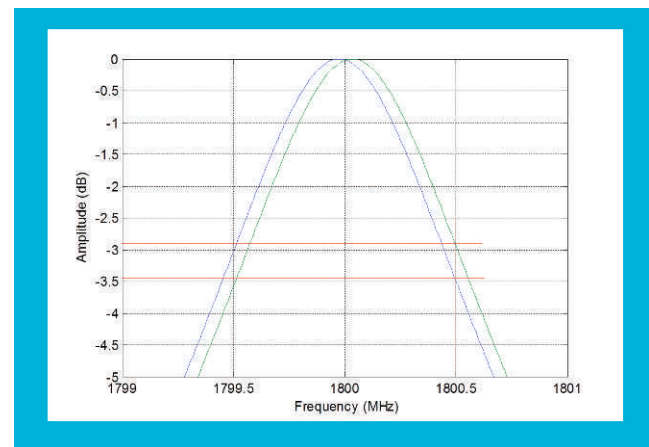


Figure 7.
Resonant cavity characteristics for Mode 1 with $Q = 1911$ showing changes in amplitude for a resonant frequency shift of ± 30 kHz.

terials or carbon fiber. Given the nature of the bug, it is likely that contact generates the nonlinear effect.

Three possible mechanisms have been listed in this category:

- ▶ Electron tunneling and semiconductor action through thin oxide layers separating contacts
- ▶ Microdischarge across voids in metallic structures
- ▶ Nonlinearities associated with dirt and metal particles on metallic surfaces

According to [2], the bug was made from silver-plated copper and had a threaded backplate that screwed into the body of the bug. In addition, the gossamer-like diaphragm was made from a material different from that of the body. Either of these two interfaces could have been the source of the nonlinearity.

If the transfer function of the nonlinearity can be represented by an n th-order polynomial series [13], then

$$V_{out} = k_1 V_{in} + k_2 V_{in}^2 + k_3 V_{in}^3 + \dots \quad (6)$$

For a sinusoidal voltage input at the illumination frequency f_i (in hertz)

$$V_{in} = \cos 2\pi f_i t, \quad (7)$$

the output voltage after simplification is

$$V_{out} = k_1 \cos 2\pi f_i t + \frac{k_2}{2} (1 + \cos 4\pi f_i t) + \frac{k_3}{4} (3 \cos 2\pi f_i t + \cos 6\pi f_i t) + \dots \quad (8)$$

For a Schottky diode, the n th coefficient k_n is scaled by $1/n!n$ [14], making the third harmonic conversion loss $L_{con} = -25$ dB.

In reality, the conversion efficiency is lower than this. For example, in [13], passive intermodulation responses measured are typically 160 dB down on the input power levels for carefully constructed broadcast antennas. For the bug, a value somewhere between these two extremes can be assumed.

To ensure that the reradiated harmonic levels could be detected above the noise, the Soviet agents would have had to broadcast a high-power directional signal.

ESTIMATED SIGNAL LEVELS

The Soviet forces had access to locally manufactured, lease-lend, and Wehrmacht radio communications equipment during World War II (WWII). Although many had transmit powers of 250 W or more, most operated in the very high-frequency band or below, so they would have been unsuitable as the illuminator. In the lower microwave bands, higher powers were available using klystrons, but these were not

generally available to the Russians even though they had been instrumental in their invention [15]. However, using conventional vacuum tube triodes to generate a signal at 600 MHz ($\lambda = 0.5$ m) would not have been efficient, so a realistic illumination power of $P_i = 25$ W is assumed.

The Yagi-Uda antenna was invented in 1926 in Japan [16] and was used in Soviet radar sets during WWII [17], so it would have been well known to Termen, who had been involved with radio-frequency electronics since the 1920s. At 600 MHz, an 8-element antenna has a gain $G_i = 20$ (13 dBi) and is 1.2 m long, so it could have easily been concealed within a van parked outside Spaso House.

The half-wave monopole Marconi antenna used by the bug would have had a gain of about $G_{bug} = 4.8$ (6.8 dBi) if it had a perfect ground plane. However, as this is not the case, a nominal gain of 3 dBi is assumed.

The link loss [10] can now be determined in decibels as

$$L_{fwd} = G_i + G_r + 20 \log_{10} \frac{\lambda}{4\pi R}. \quad (9)$$

At a range $R = 50$ m, this equates to $L_{fwd} = -46$ dB.

A small fraction of this signal is converted to the third harmonic and reradiated by the antenna. At 1800 MHz, the antenna length is about $3\lambda/2$, and the pattern starts to break up into a number of lobes, so the gain in the direction of the receiver may be reduced. Again, a nominal gain of 3 dBi is assumed.

Assuming that the receiver back in the van had a similar 8-element Yagi-Uda antenna but operates at 1.8 GHz, it would have had the same gain (13 dBi). The link loss from the bug back to the receiver calculated using Equation (9), but using a wavelength of 0.1667 m, equates to $L_{back} = -55.5$ dB.

Considering the complete path, including the link losses to and from the bug and the harmonic conversion loss, the

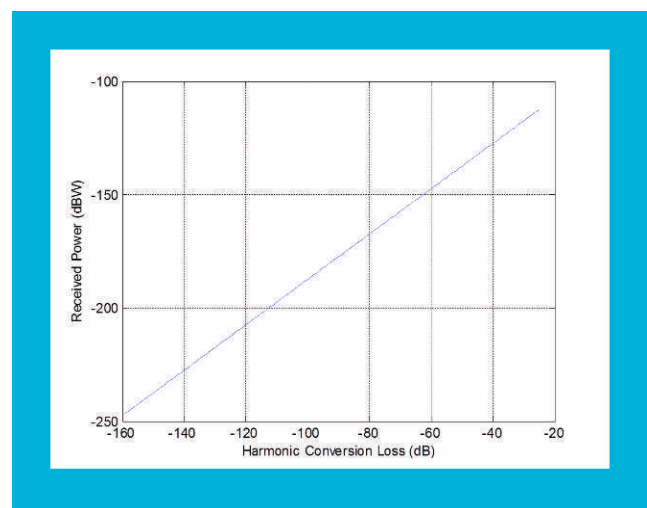


Figure 8. Received power as a function of the harmonic conversion loss for the bug at a range of 50 m.

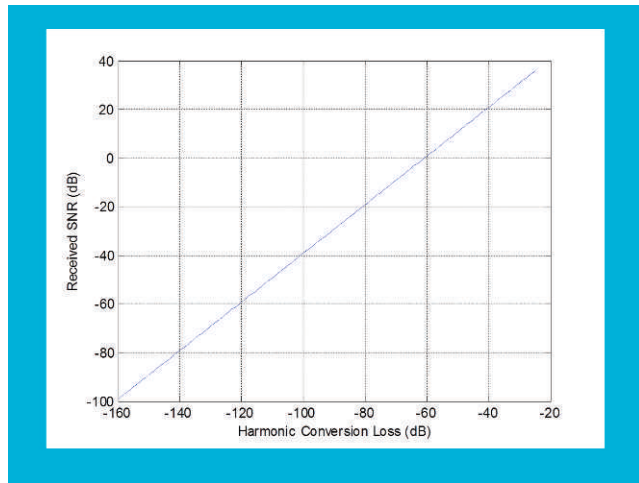


Figure 9.

SNR of the received signal from the bug as a function of the harmonic conversion loss.

expected signal level P_{rec} (in decibel watts), as shown in Figure 8, is

$$P_{rec} = 10 \log_{10}(P_t) + L_{fwd} + L_{con} + L_{back} \quad (10)$$

RECEIVED SIGNAL-TO-NOISE RATIO

The narrowband receiver needs to be able to accommodate the complete spectrum of the AM signal. This is equal to twice the highest modulating frequency [11] and thus would be about $\beta_{rec} = 6$ kHz for a 3-kHz audio bandwidth. The thermal noise N_t (in decibel watts) within this bandwidth is

$$N_t = 10 \log_{10}(kT\beta), \quad (11)$$

where $k = 1.38 \times 10^{-23}$ J/K is Boltzmann's constant and the receiver temperature is $T = 290$ K. The thermal noise is calculated to be $N_t = -166$ dBW.

Silicon point contact diodes such as the 1N21 developed during WWII for mixing and detecting microwave frequencies proved to be superior in performance to triode-based circuits [18]. It can be assumed that the Termen had access to this technology, and that one diode was used to downconvert the harmonic signal received at 1800 MHz. The conversion loss of this first mixer stage would have been at least 7 dB. A well-designed triode amplifier operating in the intermediate-frequency (IF) band would have a noise figure of 4 dB and a gain of about 20 dB. Applying the standard equation used to determine the noise figure of cascaded stages [10], [19],

$$NF = NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 G_2} + \dots \quad (12)$$

In this case $NF_1 = 10^{7/10} = 5$ is to the mixer conversion loss and $NF_2 = NF_3 = 10^{4/10} = 2.5$ are the noise figures of the subsequent IF stages. $G_1 = 0.2$ is the signal gain through

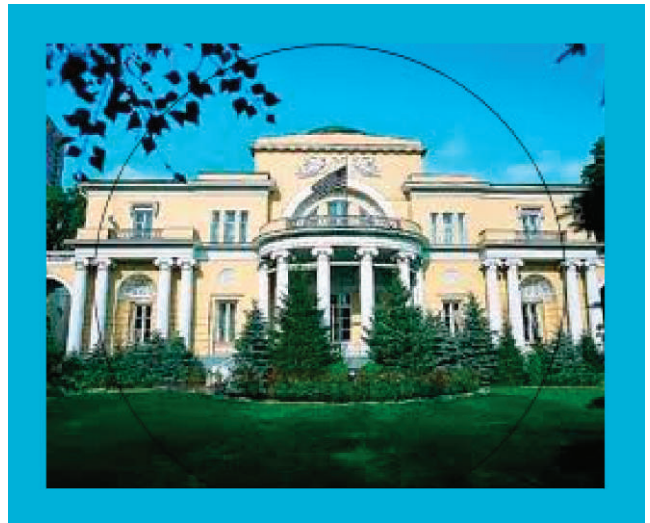


Figure 10.

Photograph of Spaso House showing the approximate diameter of the illumination beam (<http://ericajgreen.wordpress.com/>).

the mixer (the reciprocal of the conversion loss), and $G_2 = 100$ is the gain of the first IF amplifier. This equates to $NF = 5 + 7.5 + 0.075 = 12.5$ (17.8 dB) and would have defined the receiver noise figure, NF_{rec} (in decibels).

Based on the received power, the thermal noise, and the receiver noise figure, it is now possible to determine the received signal-to-noise ratio (SNR) of the signal from the bug at a range of 50 m:

$$SNR = P_{rec} - N_t - NF_{rec} \quad (13)$$

This relationship is plotted in Figure 9, which shows that a positive SNR; hence, an intelligible signal would be received for a harmonic conversion loss smaller than 60 dB.

It is certainly feasible that one of the metal-metal contacts between the cylinder and the backplane or between the cylinder and the diaphragm would have had a sufficiently nonlinear voltage characteristic to convert more than one-millionth of the incident power to the third harmonic, which would make harmonic operation of the bug a practical proposition.

BUG OPERATION AT THE ILLUMINATION FREQUENCY

To determine whether it is possible that the bug operated at the 600-MHz fundamental and that no harmonic was used, as proposed by Nikitin [1], it is necessary to compare the amount of power reflected from surrounding infrastructure to the power reradiated by the bug.

The 3-dB beamwidth of the 8-element Yagi-Uda antenna is about 41° , making the footprint diameter at 50 m equal to 35 m. The illuminator beam would have irradiated the complete frontal section of Spaso House, as well as intervening foliage, as shown in Figure 10.

From the photograph shown in Figure 10, the height of the portico section is estimated to be 8 m and that of the wings is estimated to be 6 m, making the illuminated frontal

area of the house about $A = 220 \text{ m}^2$. For an average reflectivity $\sigma^\circ = -10 \text{ dBm}^2/\text{m}^2$, which is quite low for buildings, a reflecting cross-section of $\sigma = \sigma^\circ A \approx 14 \text{ dBm}^2$ is produced.

Applying the radar range equation [20] to determine the received power in decibel watts,

$$\begin{aligned} P_{\text{echo}} &= 10 \log_{10} P_t + 2G_t + 10 \log_{10} \frac{\lambda^2}{(4\pi)^3} + \sigma - 40 \log_{10} R \\ &= 14 + 2 \times 13 - 39 + 14 - 68 \\ &= -53 \text{ dBW}. \end{aligned} \quad (14)$$

Specular returns from well-aligned windows or corners and returns from close-range foliage make this estimate very low. However, it is used as a realistic minimum value for comparison purposes.

In regard to returns from the bug, in the fundamental case, the link loss $L_{\text{back}} = L_{\text{fwd}} = -46 \text{ dB}$ and the conversion loss is smaller (ideally zero). Assuming $L_{\text{con}} = -3 \text{ dB}$, then the power received from the bug is $P_{\text{rec}} = 14 - 46 - 5 - 46 = -83 \text{ dBW}$. This is 30 dB lower than the clutter signal reflected from the house.

It is likely that the dynamic range of the receiver would have been better than 30 dB, thus allowing the modulated bug signal through without significant small signal suppression. However, moving foliage within the beam, or movement or vibrations within the house, would have resulted in fluctuations in the echo signal, which would swamp the small amount of AM generated by the bug.

CONCLUSION

The analysis presented in this article shows that the Great Seal bug has a well-coupled eigenmode around 1800 MHz, which is consistent with some of the references. This was probably one of the harmonics of the illumination source, as a high transmit power at the lower frequency would have been easier to generate. In addition, the interaction between acoustically introduced vibrations of the diaphragm would generate an AM signal that could be detected remotely.

Operation at the fundamental would probably not have been possible, as the signal from the bug would have been swamped by echoes from the building and surrounding foliage. ♦

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