# RFID-Vox: a Tribute to Leon Theremin

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**Abstract** This chapter is dedicated to Leon Theremin, the inventor of the first passive RFID tag-like device, who is more widely known as an inventor of the contactless musical instrument thereminvox. A biographical overview of Leon Theremin and his works is presented together with a concept of a wireless musical instrument named RFID-vox, which combines basic principles of thereminvox with passive UHF RFID sensor technology.

## Introduction

Radio frequency identification is an automatic wireless data collection technology with a long history [1] which is usually traced back to World War II British aircraft identification transponders [2] and the seminal paper by Harry Stockman on principles of modulated backscattered communication [3]. A person who deserves a special mention in RFID history is Leon Theremin [4], the inventor of the first passive RFID tag-like device known as the Great Seal Bug. Leon Theremin is more widely known as the inventor of the thereminvox, a contactless musical instrument (also known as simply the theremin). Interestingly enough, combining basic principles of the thereminvox with current passive UHF RFID technology allows one to create a long range contactless musical instrument ("RFID-vox") which can be played by moving RFID tags in the far field of the instrument antennas.

Section II presents a biographical overview of Leon Theremin and his work. Section III describes the RFID-vox concept and example implementations. Conclusions are drawn in Section IV.

## Leon Theremin

On April 25, 1930, Carnegie Hall was very busy. Everyone wanted to see the concert performed by ten musicians, each simultaneously playing a thereminvox, a new electronic musical instrument invented by a Russian who organized the concert and was playing in it himself [5]. Thirty years later, in 1960, US ambassador Henry Cabot Lodge, Jr. was showing at the United Nations meeting a passive eavesdropping device that was discovered in US embassy in Moscow, Russia

What links those two events? The creator of both the thereminvox and the Great Seal bug was the same person – a prominent inventor and musician, Leon Theremin. We invite a reader to take a brief look at his extraordinary life. For more detailed information, we refer a reader to the article [6], the book [7], and the excellent documentary movie [8].

Lev Sergeevich Termen (he became known as Leon Theremin after he came to America in 1927) was born on August 15, 1896 in St. Petersburg, Russia. He started learning music and physics at the early age, and then went to study physics and astronomy at the University of St. Petersburg. He also studied cello at the St. Petersburg Music Conservatory. During World War I, he was drafted, graduated from the Officers' Electro-Technical School and served as an officer. After the Russian Revolution of 1917, he worked on equipment for the first radio stations of Soviet Russia. His life, like the lives of many others, was affected by the revolution: he spent time in prison in 1919-1920 after being accused of counter-revolutionary activity.

In 1920, he joined Ioffe Physical Technical Institute where he became the head of the new experimental laboratory and started working on high frequency measurement methods. He found that the movement of one's hands affects the capacitance of electronic circuits and thus can be used to control oscillator pitch and volume. Using this effect, Leon Theremin created the first contactless musical instrument, originally called the aetherphone (and later the thereminvox or simply the theremin). The basic physics of the thereminvox has been analyzed in detail in [9]. Based on the same capacitance sensing effect, he also invented an alarm system. In 1922 he showed both inventions to Vladimir Lenin who liked them very much. In this period of time, Leon Theremin also worked on mirror-drum based mechanical television and successfully demonstrated prototypes. He travelled across the country to demonstrate his inventions and was often referred to as the "Soviet Edison".

To promote his inventions, Leon Theremin went on an international tour, visiting Germany, England, France, and arriving in the United States in 1927. The thereminvox created a sensation there [10]. Leon Theremin established a laboratory in Manhattan where he worked on the thereminvox and other electronic musical instruments (electronic cello, terpsitone, etc.). In 1928, he received a US patent for the thereminvox [11] and sold it to RCA which began producing his instrument [12]. The instruments were expensive: in 1930 the cost of the complete system with speakers was approximately $230 which corresponds to $3,000 in today's dollars. Only about 500 instruments were produced and sold.

In 1930 Leon Theremin demonstrated ten thereminvoxes on the concert stage at Carnegie Hall [5], and in 1932 he conducted the first electronic orchestra performance there [13]. In that time period, Theremin closely interacted with many famous scientists and musicians, including Albert Einstein (who played violin), composer Joseph Schillinger, and thereminvox virtuoso Clara Rockmore, who helped him to promote his instrument.

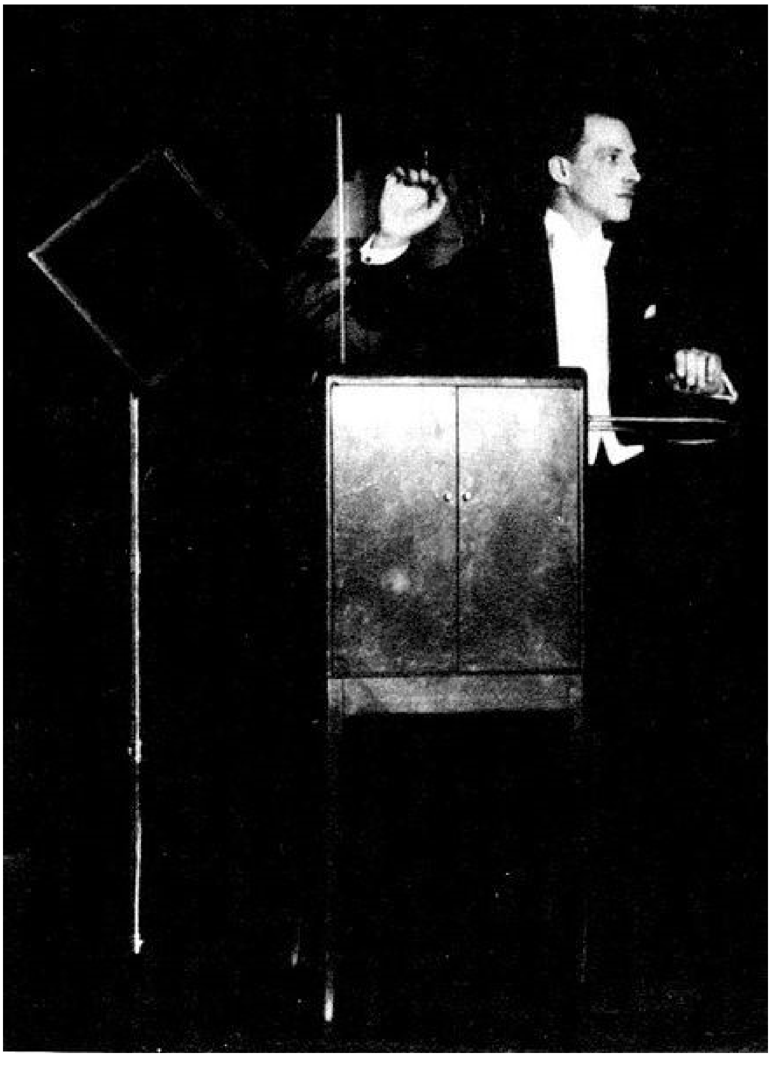

**Fig. 1.** Leon Theremin plays theremin (1924). Courtesy Wikimedia Foundation.

In 1931 he became a Vice-President of TeleTouch corporation which sold his patented "radio watchman" [14], a capacitance-based alarm system. One of its customers was Alcatraz prison. In 1936, he received his third US patent, for an electrical clock run by DC current [15]. In 1938 Leon Theremin married African American ballet dancer Lavinia Williams who bore him twin daughters. (He had divorced his first wife, Katia Konstantinova, soon after he arrived to the US).

In September 1938, he abruptly returned to the Soviet Union. Whether he returned voluntarily or was forced to is a subject of debate. In March 1939 he was arrested and sentenced to 8 years in prison. He was sent to the camp in Magadan, Kolyma, one of many in GULAG prison and labor camp system [16, 17]. Leon Theremin would have probably died there, as the survival rate in Stalin's camps was very low. Fortunately, in 1940, he was transferred to Moscow secret research and development laboratory, an elite part of the prison system, where he remained until 1947 working on various military projects. He worked with Sergei Korolev, who later became a key figure in the Soviet space program. Korolev went on to develop the rocket for the Sputnik launch and started the Soviet lunar program [18].

One of the projects which Leon Theremin worked on at prison became known as the Great Seal Bug [19]. In 1945, Soviet Young Pioneers (analogous to Boy Scouts and Girl Scouts) presented to the US ambassador in Moscow a carved wooden replica of the Great Seal of the United States. This gift contained a passive listening device which was finally discovered by accident only in 1952, seven years later. The device consisted of a monopole antenna connected to a resonator with a flexible sound-sensitive membrane. The audio in the room caused geometric deformations of the microphone, which in turn changed the antenna's RF reflection coefficient. The net effect was that the apparatus backscattered an incident carrier wave radio frequency signal (originating from a transmitter outside the embassy) while modulating it with the voice of those present in the room. This device was essentially the first long range passive UHF RFID tag. Modern RFID tags use basically the same operating principles of modulated backscatter. US ambassador Henry Cabot Lodge, Jr. demonstrated the Great Seal bug during the 1960 UN General Assembly session as an example of Soviet espionage. A replica of the Great Seal Bug is currently on display at NSA National Cryptologic Museum in Annapolis Junction, MD [20].

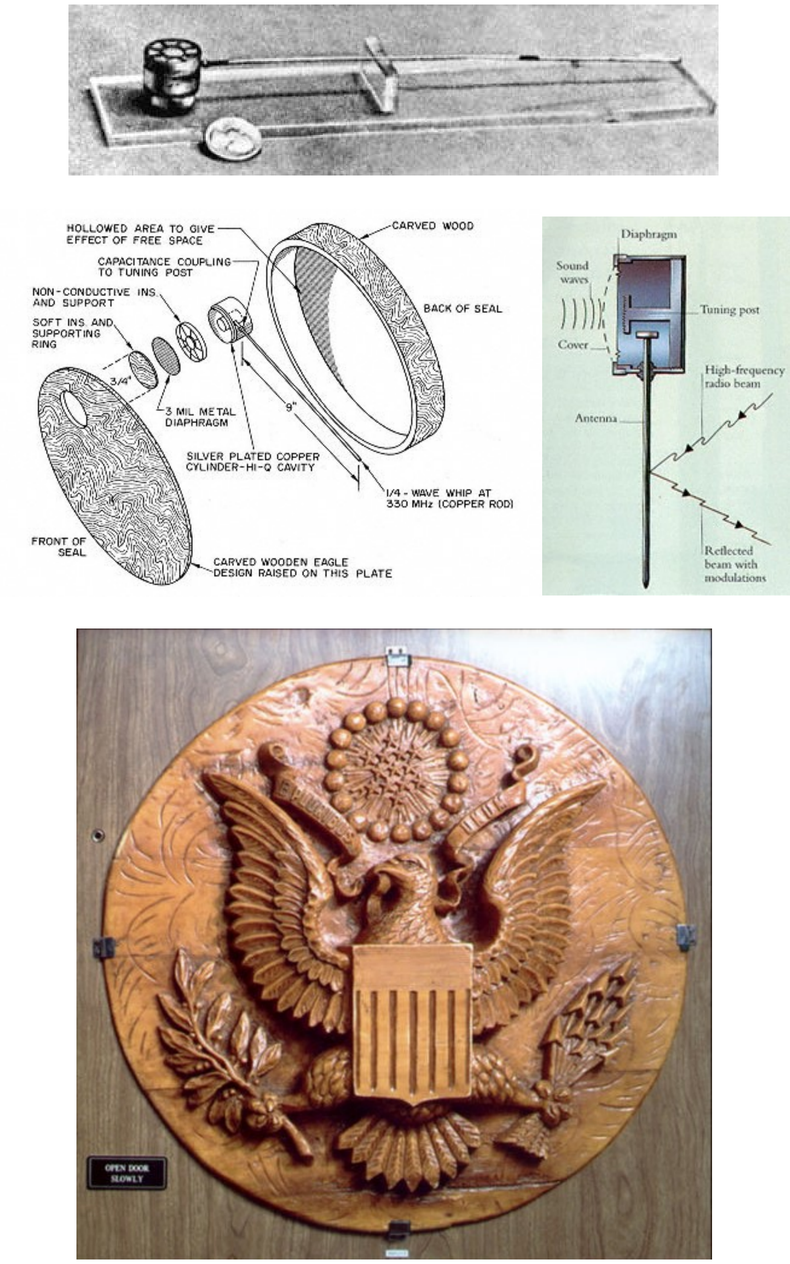


**Fig. 2.** The Great Seal bug: the antenna with the resonator (top), principle of operation (middle), the US Great Seal with the embedded device (bottom). Courtesy Wikimedia Foundation.

In 1947, Leon Theremin was freed and awarded the Stalin medal of the 1st degree for his work on eavesdropping devices (his other invention was Buran, an eavesdropping system which used infrared beam to detect glass vibrations caused by sounds inside the room). After that, Leon Theremin continued to work on different military projects. He married for the third time and had twin daughters. In 1964, he joined Moscow Conservatory where he worked on various electronic musical instruments. In 1967, an American journalist found him in Russia, interviewed, and published an article about him in New York Times [21]. It was the Cold War era. After the article came into print, Leon Theremin was immediately fired, his laboratory was closed, and most of his instruments were destroyed. For some time, he could not find any job. Finally, with help of his friends, he started working as a technician and lab assistant at the Physics Department of Moscow State University where he remained for the rest of his life.

In 1991, Steven M. Martin filmed a famous documentary about Leon Theremin [8] and brought him to visit the US where Leon met again Clara Rockmore, after more than 50 years. Lavinia Williams, his wife whom he never saw after 1938, died in 1989, just two years before his visit. In 1991, Stanford Universty awarded Leon Theremin a Centennial Medal for contributions to electronic music. Leon Theremin died in Moscow on November 3, 1993, at the age of 97.

## RFID-vox

The thereminvox still holds an important place in electronic musical instruments. It was used for composing music by the Beach Boys (*Good Vibrations,* 196*6*), in Hollywood movies (*The Day the Earth Stood Still*, 1951; *It Came from Outer Space,* 1953), etc. Theremin amateur societies are abundant today [22-24], thereminvoxes continue to be built [25, 26], patents based on original Theremin idea continue to be filed and issued [27], and even Thereminist robots are being developed [28]. There, of course, exists a variety of other electronic musical instruments, both thereminvox-based [29-31] and using other principles [32-34].

Leon Theremin once said in an interview about thereminvox: “I conceived of an instrument that would create sound without using any mechanical energy, like the conductor of an orchestra. The orchestra plays mechanically, using mechanical energy; the conductor just moves his hands, and his movements have an effect on the music artistry” [35]. The near field nature of the original thereminvox construction required a player to be in the direct vicinity of volume- and pitch-controlling antennas (it is a form of electric field sensing [36]). Interestingly enough, current UHF RFID technology presents another way to realize Leon Theremin’s vision of creating a contactless musical instrument which can be played remotely, like a conductor guiding an orchestra.

The main concept of this instrument (we call it “RFID-vox”) is illustrated in Fig. 3. A person plays it by moving one or more tags (passive or semi-passive) in the far field of the reader antenna system. Tag signals from the RFID reader control the electronic sound characteristics, such as volume and pitch, like in a classical thereminvox. The reader can provide to the musical controller either analog, or digital signals, or both. Examples of analog tag signals can be the received signal strength (RSSI) and the phase of backscattered tag signal, readily available [37, 38] in commercial Gen2 (ISO-18000 6C [39]) UHF RFID readers. Examples of digital tag signals can be tag ID or data from sensors integrated into the tags. The Gen2 protocol allows for the tag to be read hundreds of times per second. Mapping and linking the received input from each tag to the sounds produced by the instrument is by itself a rich area of computer music research [40, 41]. Multiple tags could be used control many musical parameters or play an orchestra of such instruments. Using the latest passive Gen2 ICs with a sensitivity on the order of -20 dBm [42], such an instrument can be played at a distance of more than 20 meters. With the semi-passive (battery-assisted) ICs [43, 44], the operating range can be extended even further.

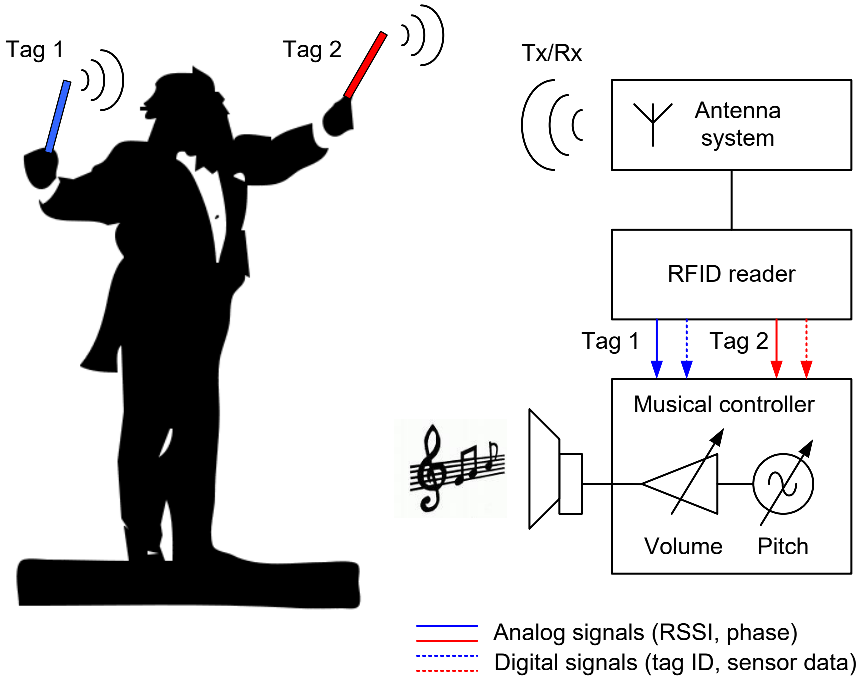


**Fig. 3.** RFID-vox concept: analog and digital. Courtesy Wikimedia Foundation for person silhouette.

A simple analog version of RFID-vox can easily be realized using a Gen2 reader (which provides tag RSSI and phase readings) and a computer with a sound card. The RFID-vox can be played, for example, using two sticks, similar to conductor's batons, with embedded dipole-like RFID tags, as shown in Fig. 3. The tag in each baton will have its own ID, which allows one to associate the received RSSI and phase with the particular tag. The received RSSI and phase of the tag signals change with the tag position (in free space, both change monotonically with the distance to the reader antenna) and can be directly linked to control the sounds (volume and pitch). As an alternative, tag location can be calculated using various methods [37, 38] and mapped to a virtual piano keyboard space in front of the player. Note that unlike some well known wireless controls for computer, such as Wii Music [45], these batons can be purely passive devices without any batteries. Of course, playing such an analog instrument will require a certain skill, just as a certain skill is required to play a thereminvox. In the thereminvox, one's body and hands strongly interact with the near field of thereminvox antennas and affect the way the instrument responds to the player. In the RFID-vox, the interaction happens in the far field, and if the tags are detached from the hands (like in baton sticks), they are not affected by one's body as much. However, the complexity of the propagation channel (including reflections, polarization mismatch, and other effects) will probably make the task of learning how to play RFID-vox equally challenging.

Digital RFID-vox instruments could also be implemented. The digital identification capability of RFID suggests using different physical objects as input devices, each of which could be associated with a unique sound or instrument. Rather than implementing the sensing in an analog fashion, one could build sensors into the RFID tags, and communicate the sensor data as well as the ID digitally.

A first digital version of an RFID-vox was realized using our single bit tilt sensor called "the α-WISP" [46]. An α-WISP consists of two UHF RFID tag ICs multiplexed by tilt sensing switches to a single antenna. Due to this arrangement, in one tilt state the α-WISP returns its first ID to the reader; in the other tilt state, it returns a second ID to the reader. If the reader software knows that the two IDs are associated with the same object, then the reader learns one bit of sensor information, encoding the tilt of the object, from each read event.

An α-WISP was affixed to a cup. When the cup transitions from the first tilt state to the second, a musical sound associated with the new tilt state is triggered by the reader. Thus as the object is tipped back and forth, it plays its two sounds. A second α-WISP, affixed to a second cup, is able to trigger completely different sounds: the unique IDs provided by the RFID tag allow each distinct physical object to be associated with its own characteristic sound set. A video of the α-WISP-based musical instrument is available online [47].

A more sophisticated instrument was created using a more sophisticated RFID sensor tag. Our WISP [48] sensor is a fully passive (RF powered), programmable UHF RFID tag that includes a 3 axis accelerometer, as well as other sensors. The sensor values can be mapped to pitch and volume, by analogy with the thereminvox, but these controllers could also be used in countless other ways as well. As a first exploration of such an instrument, we mapped the WISP's tilt to a continuously generated pitch. As the WISP tilts, the pitch being played changes. A video of this experiment is available online [49]. A value thresholding method is used to map one dimension of the acceleration vector produced by the WISP to a musical scale degree (note index in a musical scale). Any particular musical scale (e.g., Major or Minor) may be selected, or alternately all twelve tones may be used. A small amount of threshold hysteresis makes for cleaner note transitions in the presence of measurement noise. A second dimension of the acceleration vector adjusts the volume of the tones produced.

The relatively low cost of RFID tags could enable many collectible input devices (which might even look like toys rather than musical instruments, as has been described in [50]), each of which could trigger unique musical behaviors. RFID-vox devices could enable new types of musical input devices that could find many applications. For example, novel musical controllers, such as the guitar controller used in the music game Guitar Hero [51], combined with proper music mapping algorithms, can also allow non-skilled musicians to enjoy the experience of playing music or used for children's musical education [52].

## Conclusions

This book chapter was written as a tribute to Leon Theremin, a great inventor and an extraordinary person who lived an amazing life and stood at the roots of electronic musical instruments as well as modulated backscatter technology. Quoting Nick Holonyak, inventor of the light-emitting diode (LED): “Theremin (Lev Termen) should be known for more than just a musical instrument” [53].

It is exciting to see that new technologies (such as Gen2 UHF RFID) combined with old principles (such as the ones used in thereminvox) can open up a window for novel applications, such as wireless contactless musical instruments. As an example of such application, we described RFID-vox instruments (both analog and digital versions) that can be readily built with existing technology.

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