

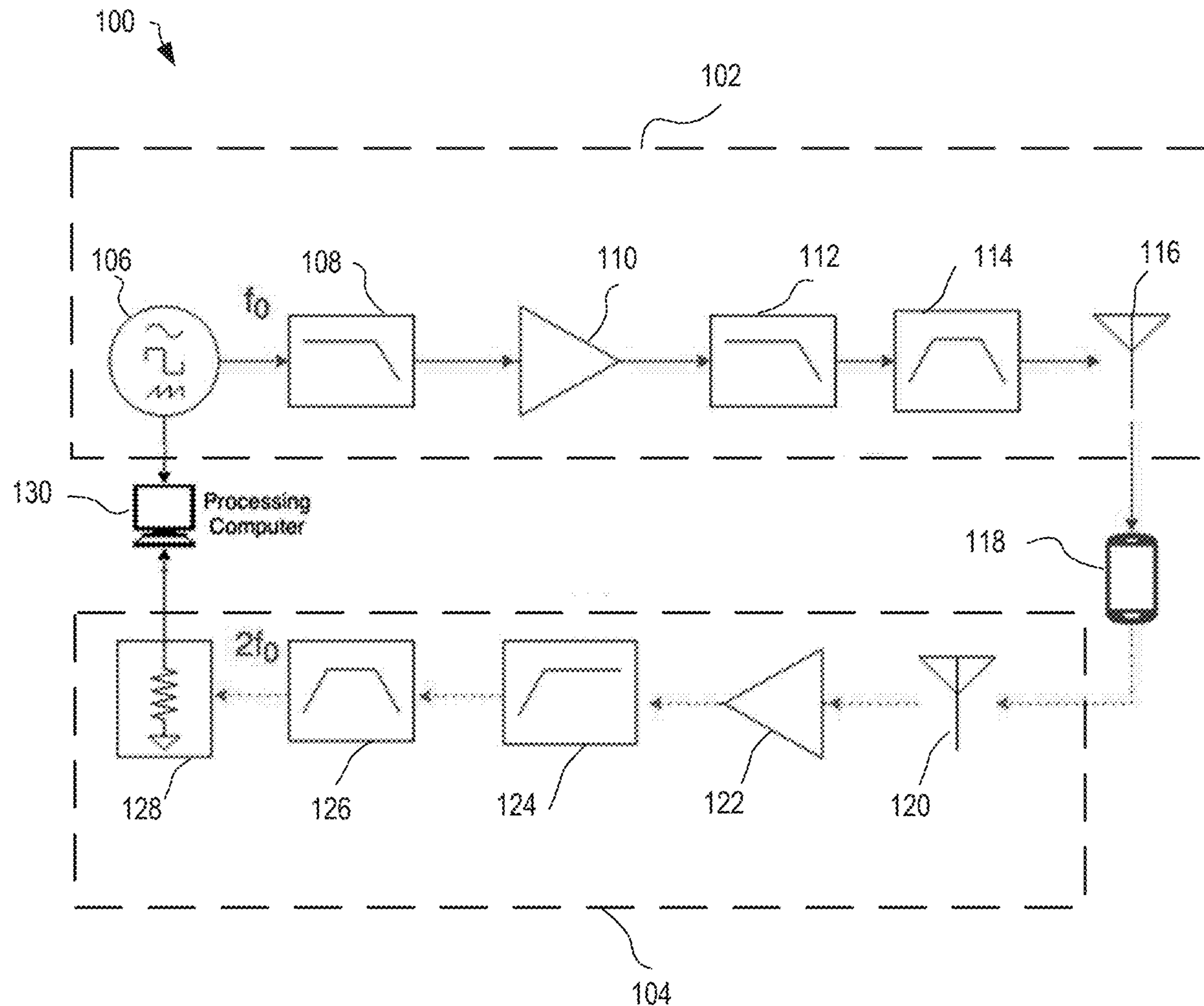
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(19) **United States**(12) **Patent Application Publication**
Arguello et al.(10) **Pub. No.: US 2025/0362406 A1**(43) **Pub. Date: Nov. 27, 2025**(54) **HARMONIC RADAR FOR WIRELESS
BATTERY DETECTION**(71) Applicant: **The Trustees of Dartmouth College,**
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David Kotz, Hanover, NH (US)**G01S 7/292** (2006.01)**G01S 7/41** (2006.01)**G01S 13/76** (2006.01)(52) **U.S. Cl.**CPC **G01S 13/887** (2013.01); **G01S 7/282**
(2013.01); **G01S 7/292** (2013.01); **G01S 7/41**
(2013.01); **G01S 13/76** (2013.01)(21) Appl. No.: **19/216,352**(22) Filed: **May 22, 2025****Related U.S. Application Data**(60) Provisional application No. 63/651,278, filed on May
23, 2024.**Publication Classification**(51) **Int. Cl.****G01S 13/88** (2006.01)**G01S 7/282** (2006.01)

(57)

ABSTRACT

A harmonic radar system for detecting a battery may include a signal generator for generating one or more transmit radio frequency (RF) signals, one or more low-pass filters for removing harmonics from the transmit RF signals, a transmitting antenna for sending the transmit RF signals into an environment, a receiving antenna for receiving signals reflected or re-radiated by the battery in the environment in response to the transmit RF signals, one or more high-pass filters for filtering the received signals, and a spectrum analyzer for identifying a harmonic frequency of the transmit RF signals in the filtered signals.



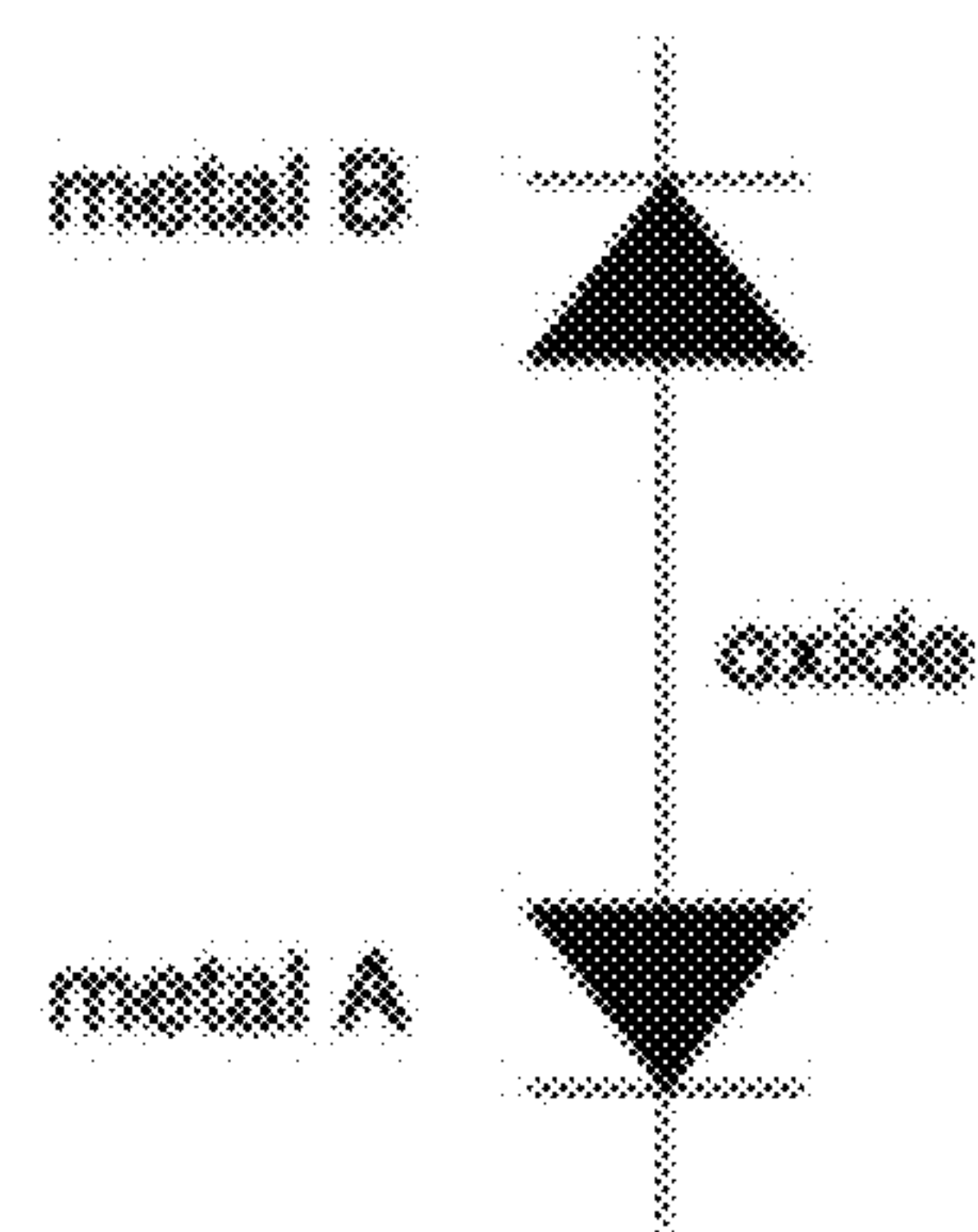


FIG. 1A

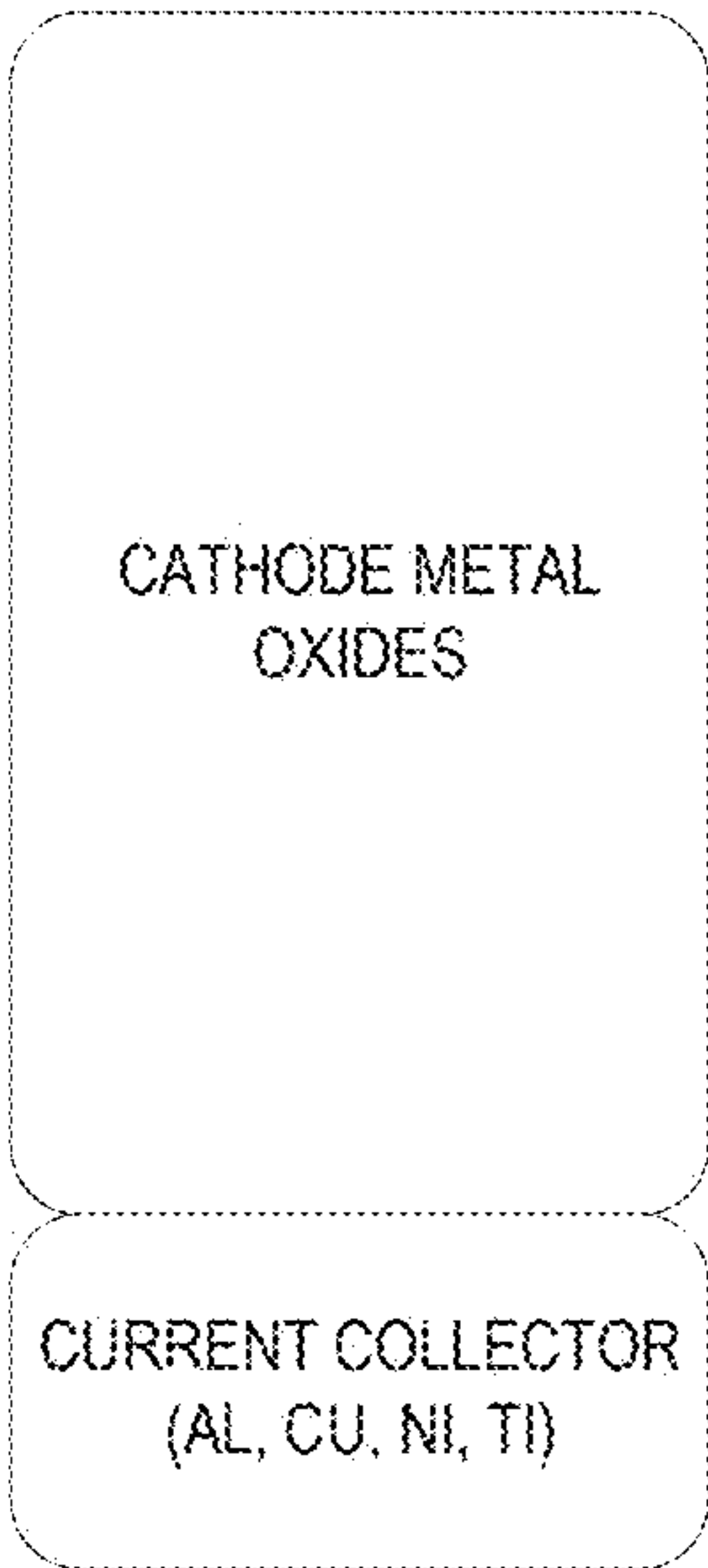


FIG. 1B

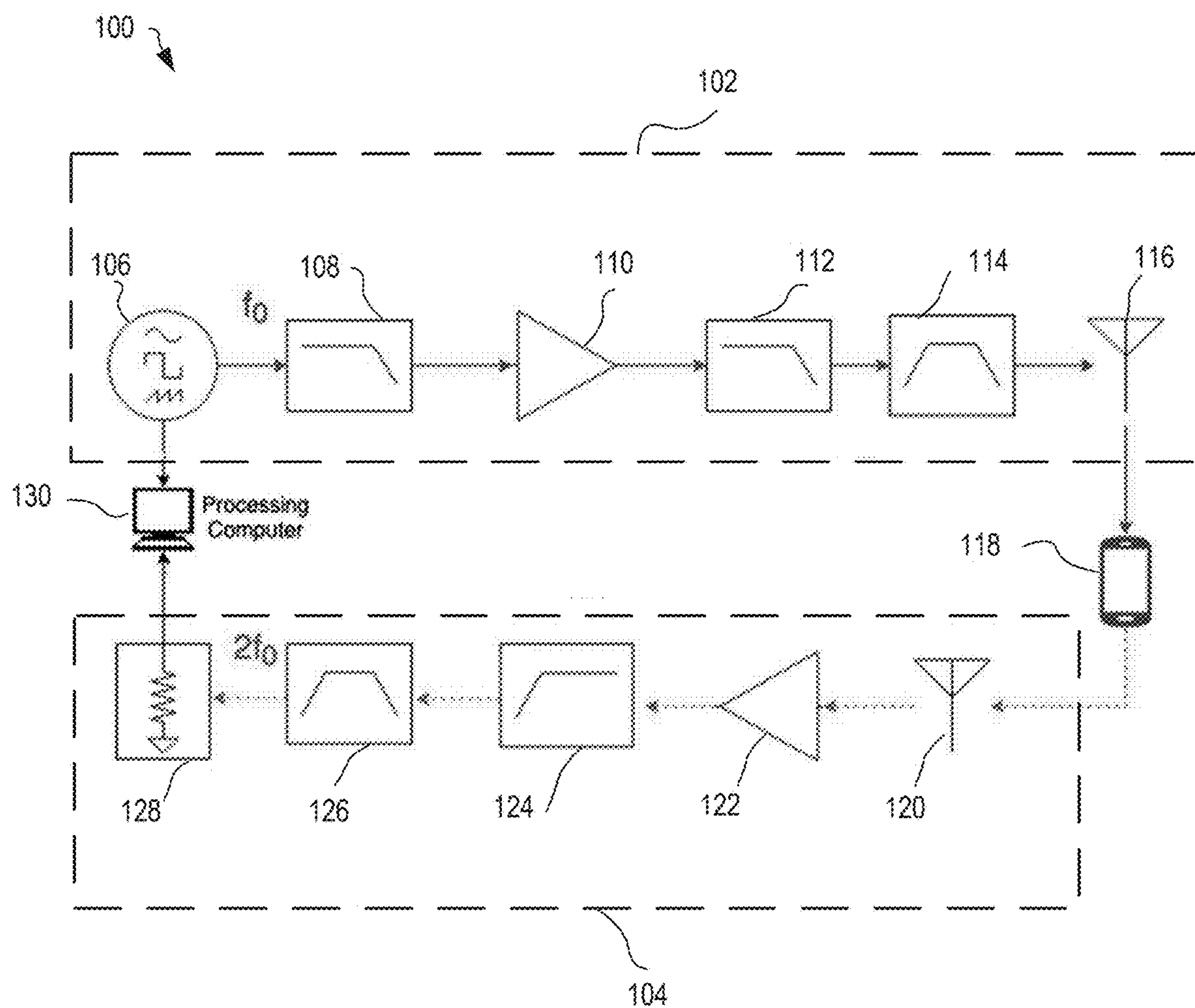


FIG. 2

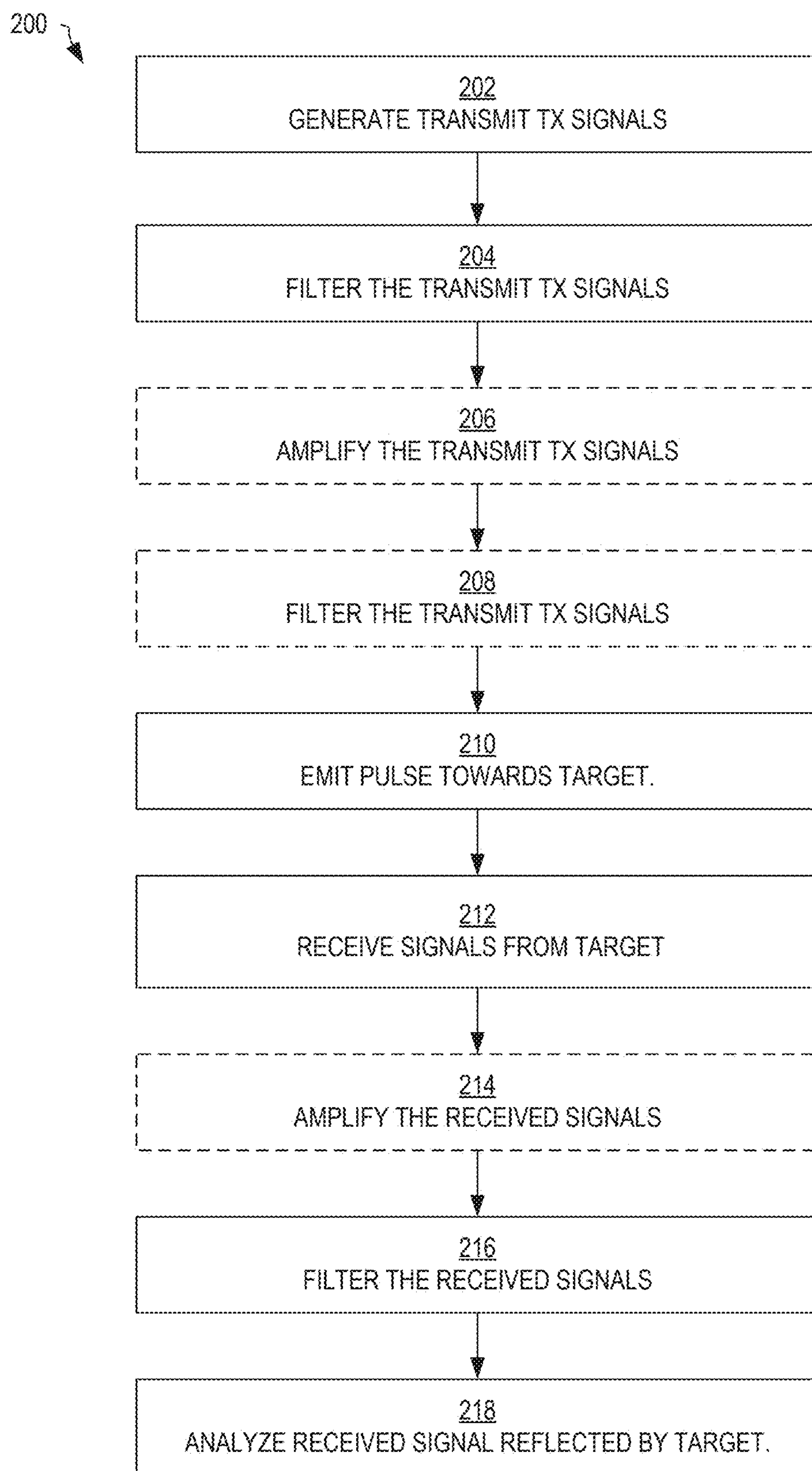


FIG. 3

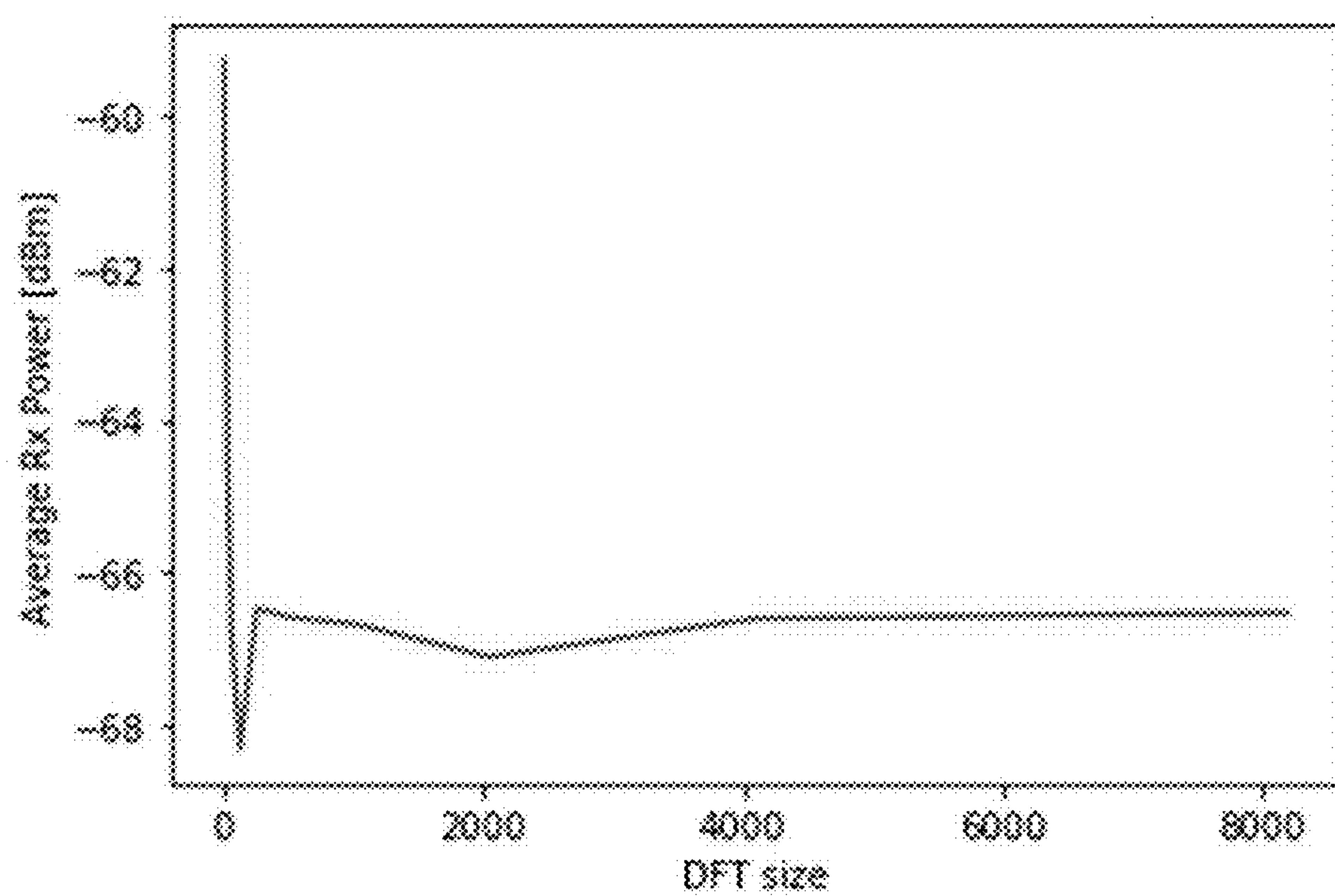


FIG. 4

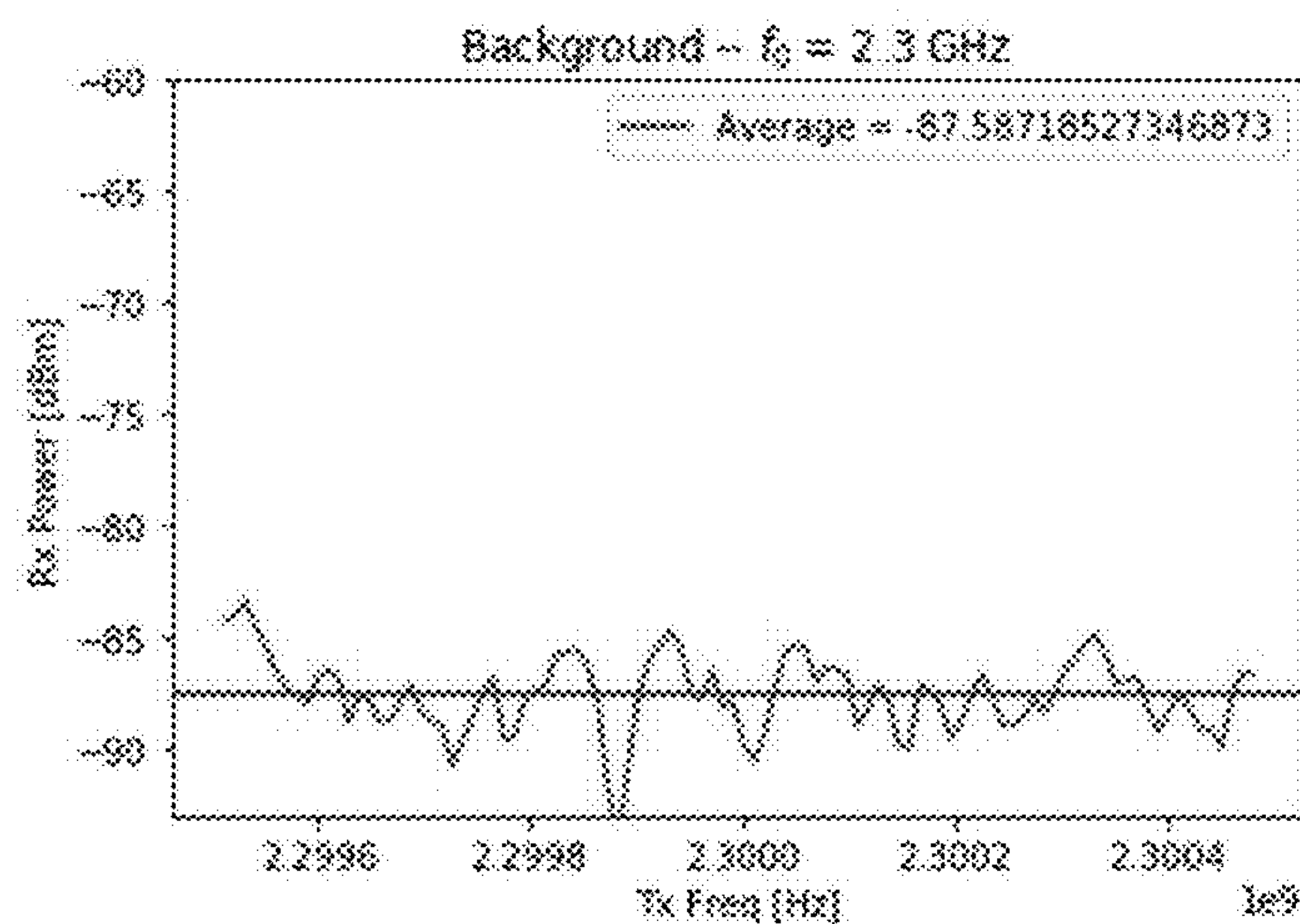


FIG. 5A

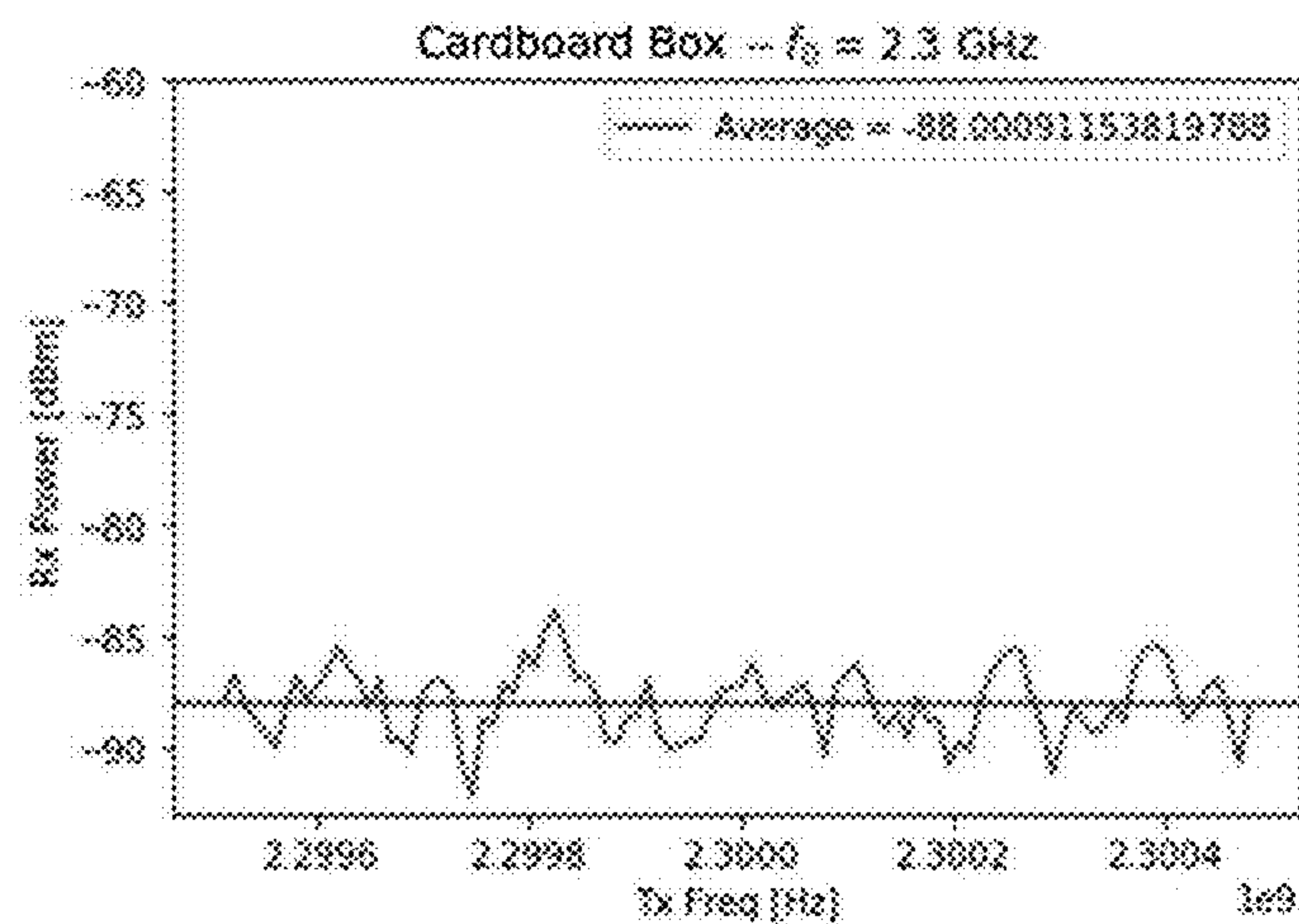


FIG. 5B

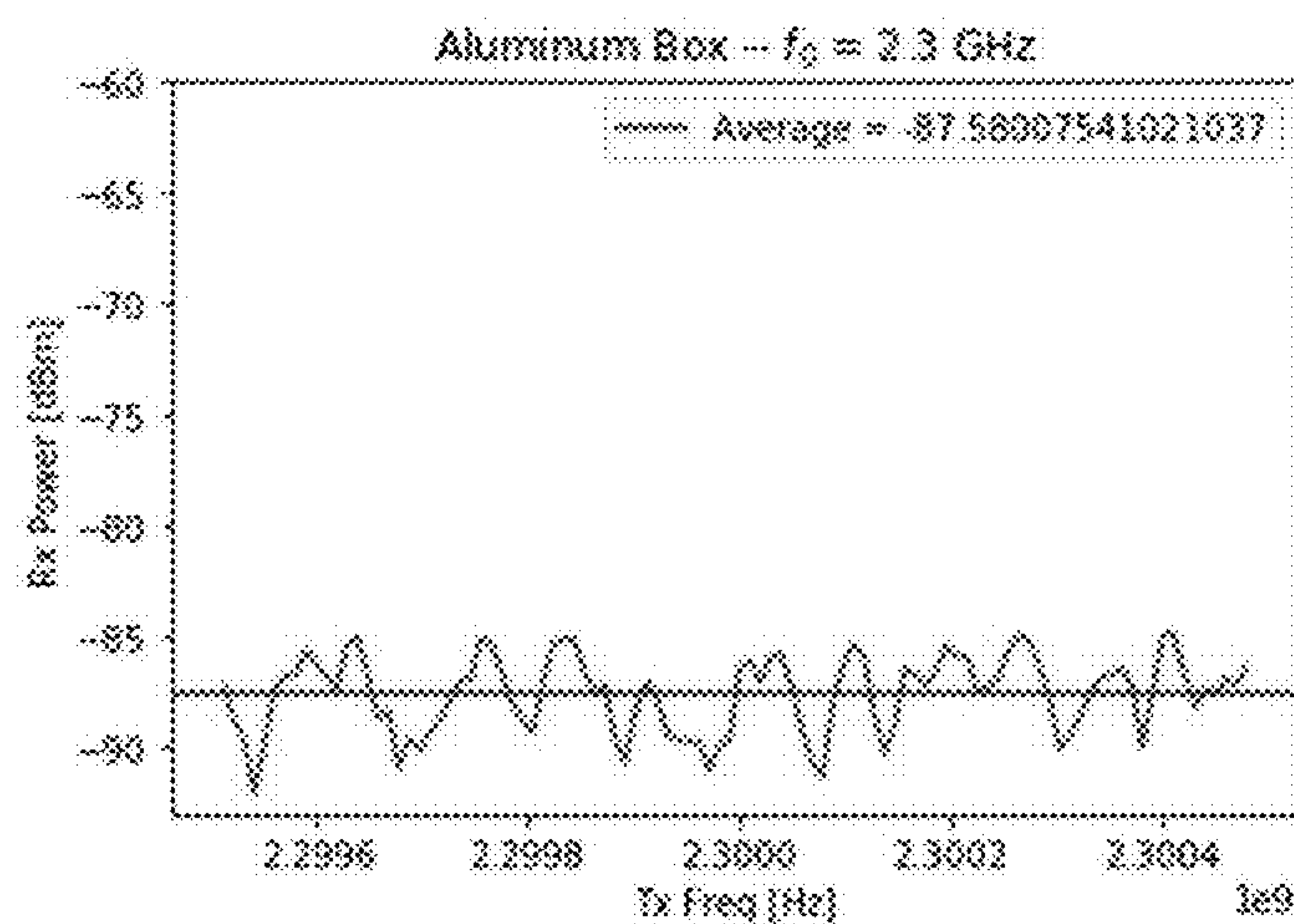


FIG. 5C

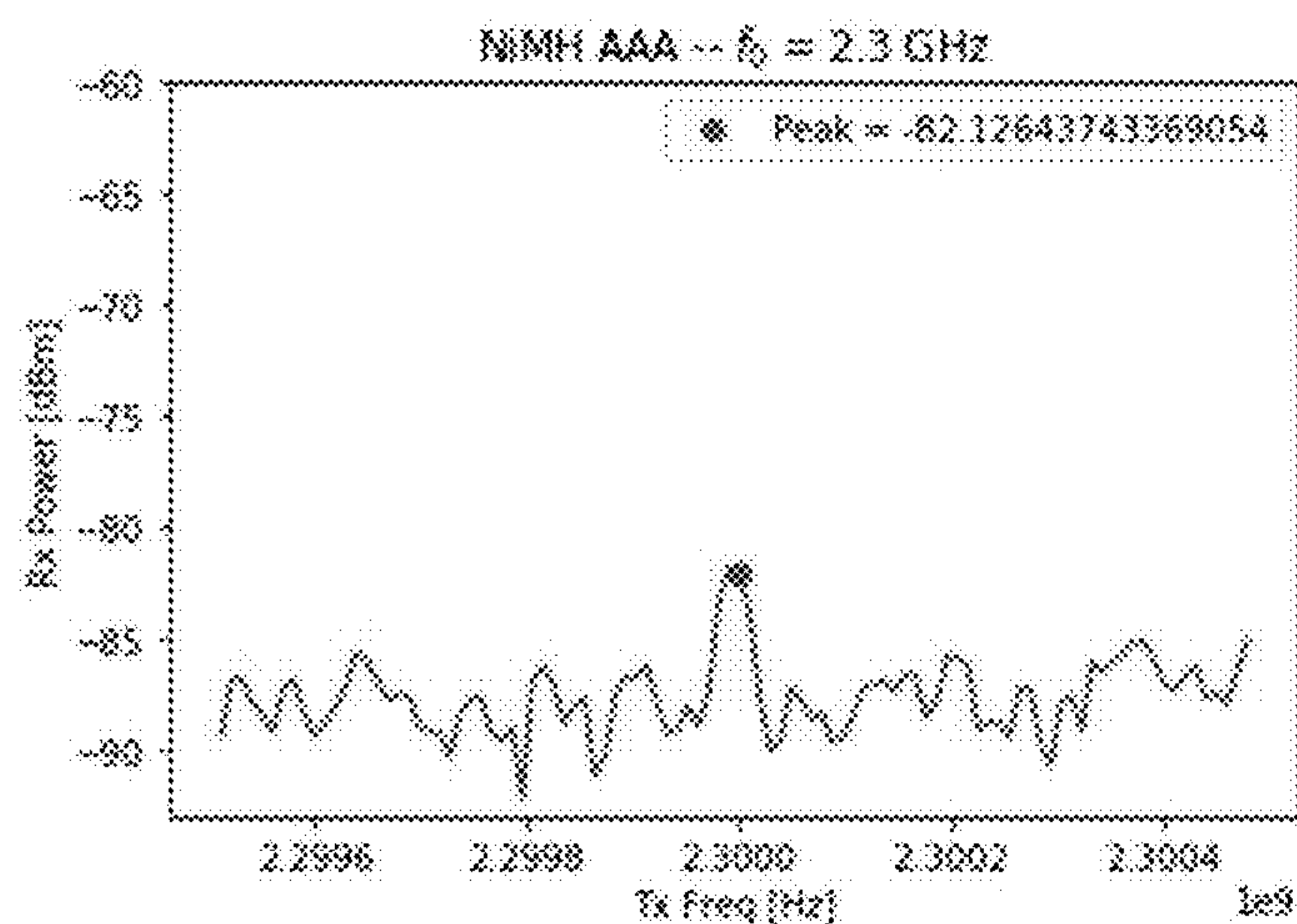


FIG. 6A

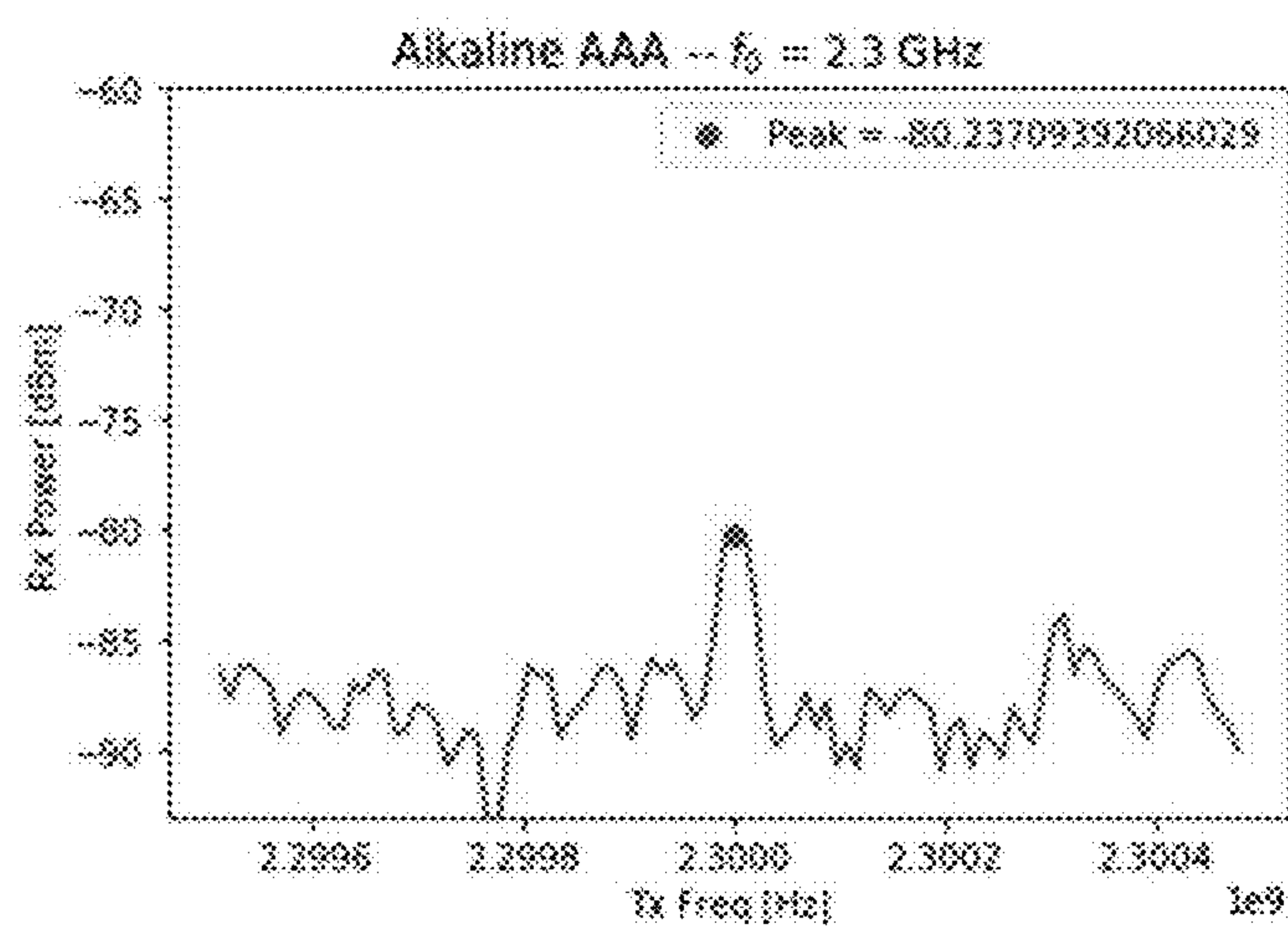


FIG. 6B

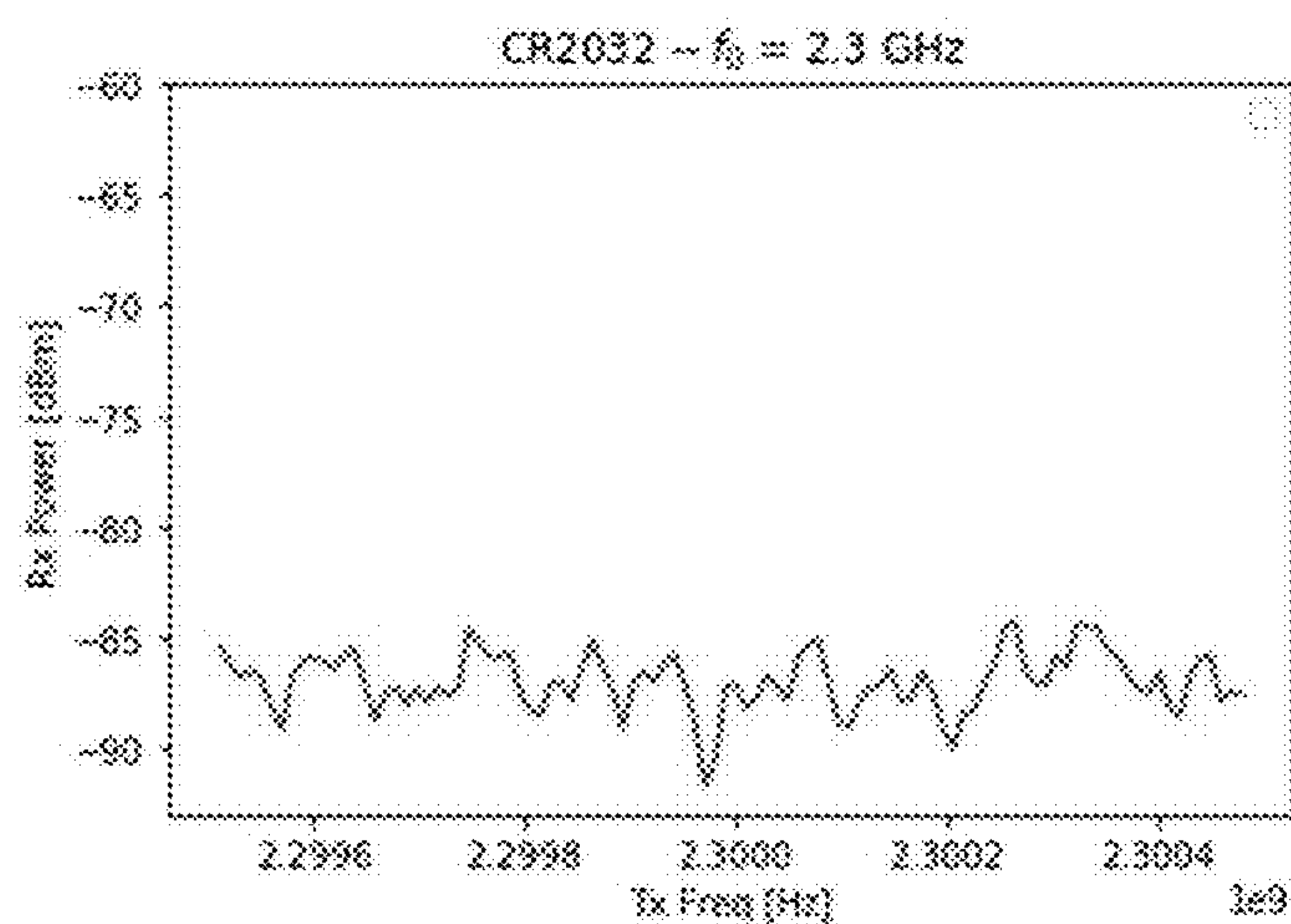


FIG. 6C

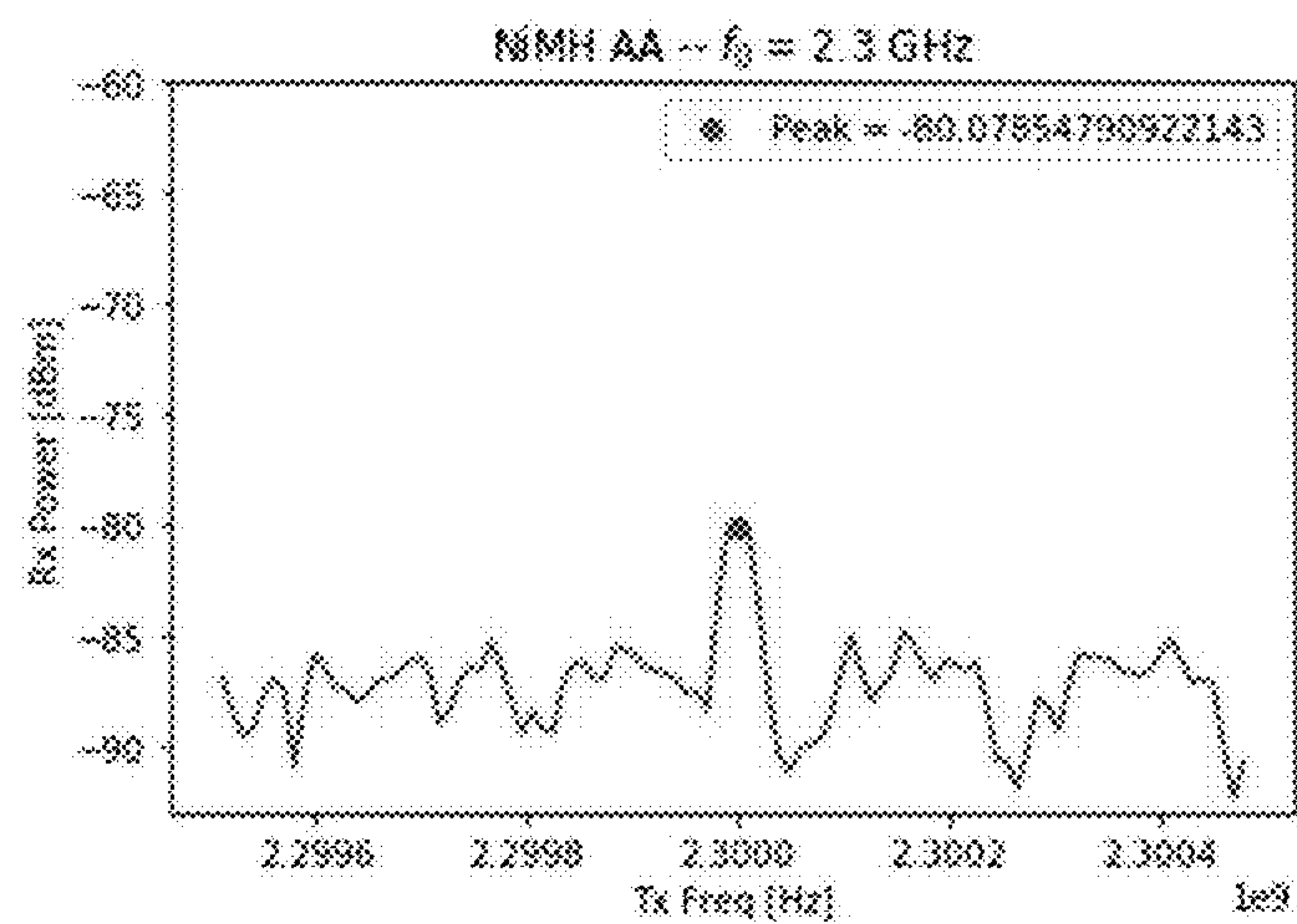


FIG. 6D

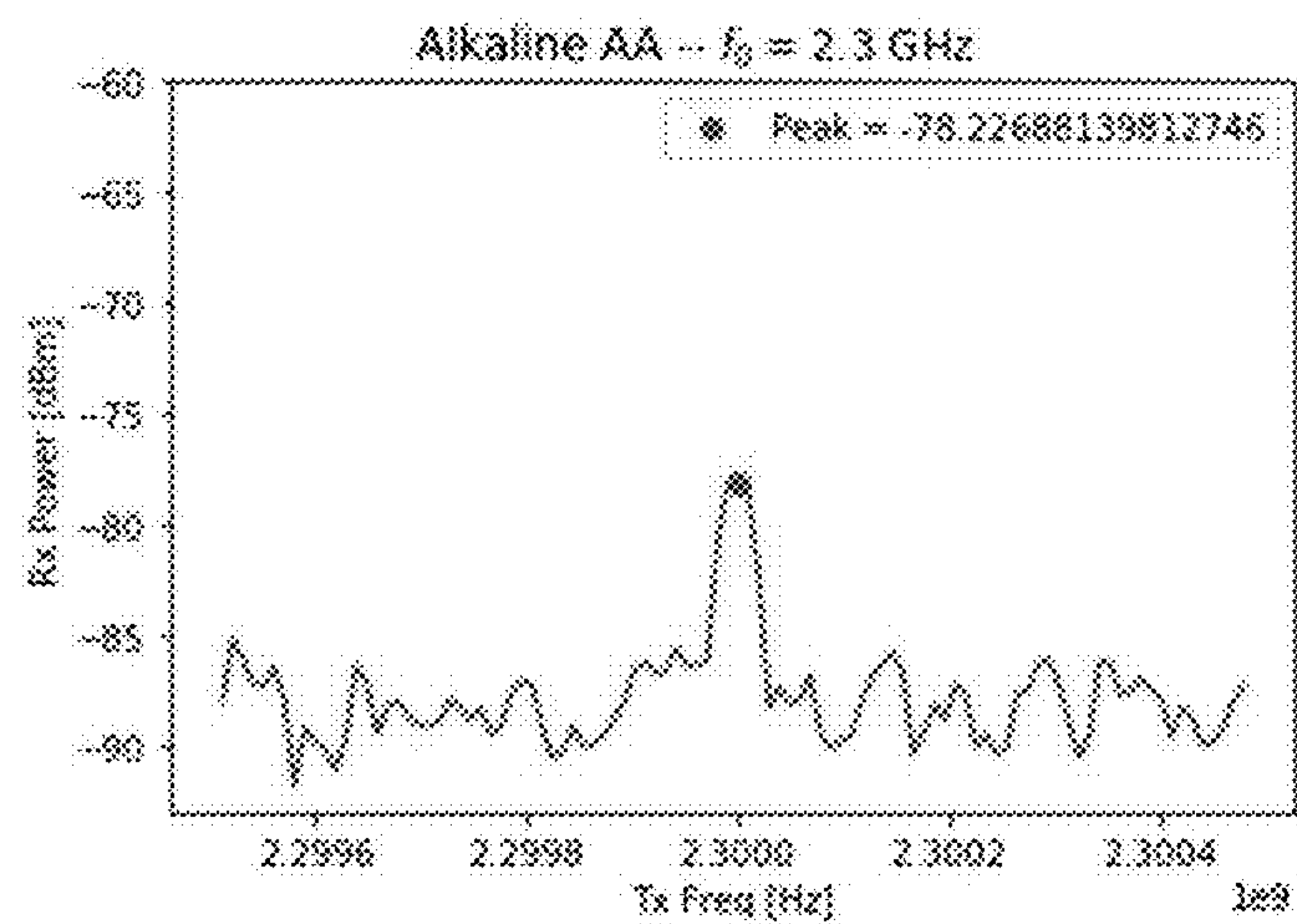


FIG. 6E

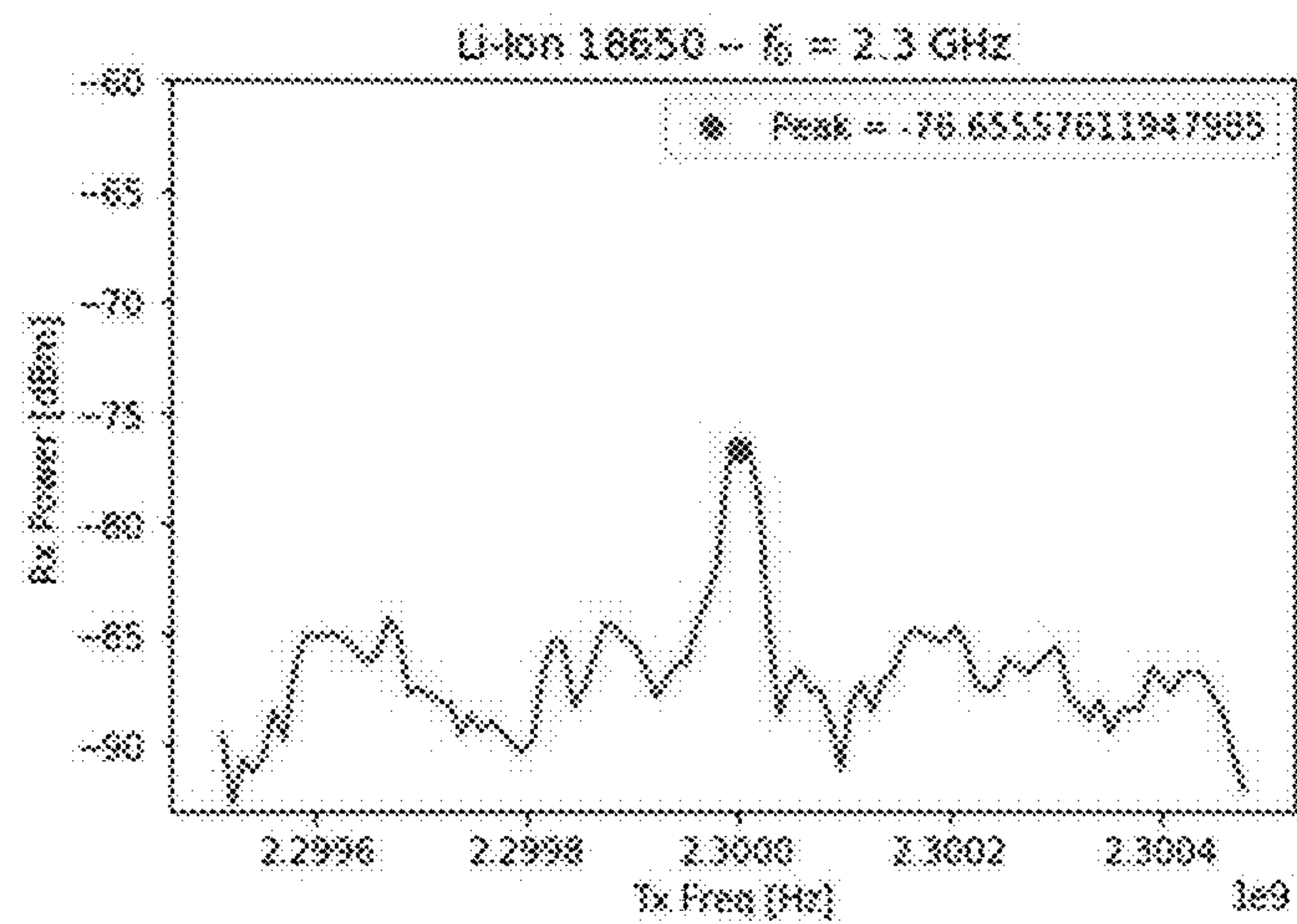


FIG. 6F

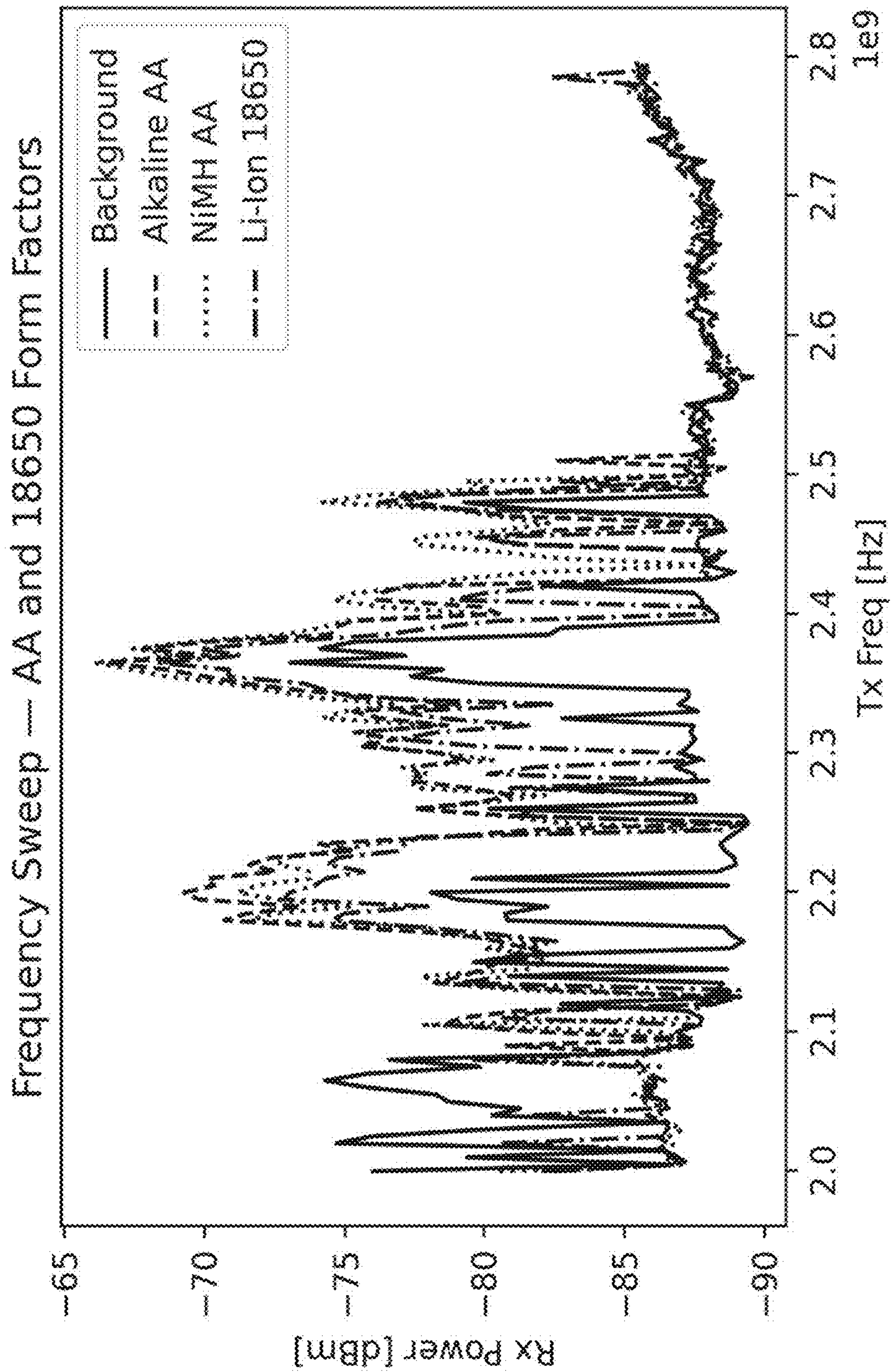


FIG. 7

HARMONIC RADAR FOR WIRELESS BATTERY DETECTION

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Application No. 63/651,278 filed May 23, 2024, incorporated herein by reference in its entirety.

U.S. GOVERNMENT RIGHTS

[0002] The U.S. Government has certain rights in this invention as provided for by the terms provided by the U.S. National Science Foundation under grants 1955805 and 2030859.

BACKGROUND

[0003] Data about users is collected almost continually by phones, cameras, Internet websites, and other electronic devices. The advent of so-called ‘Smart Things’ or the Internet of Things (IoT) now enables ever-more sensitive data to be collected about a local environment, and that data can be used to infer characteristics about nearby people. As the number of deployed devices grows, it will become increasingly difficult for people to know if they are being observed by these devices. This problem is particularly salient as people become the occupants (perhaps temporarily) of a new space such as a hotel, conference room, or rental unit. In that case, the person may not be aware of all devices present in the environment. In some cases, devices such as hidden cameras may be purposely obscured to escape detection. Conversely in smart environments with dozens or hundreds of deployed devices, it may become extremely difficult for an administrator to maintain the location and status of every device in a space.

[0004] In addition to the security and privacy risks raised by the presence of IoT devices ubiquitously and unobtrusively collecting data, battery cells are a fire hazard in environments such as checked bags in airplanes as well as e-waste recycling plants. Moreover, separating batteries from electronic waste is critical for the correct extraction of precious metals from discarded electronics. Existing methods for detecting batteries in cluttered environments rely on expensive X-ray machines and computationally intense machine-learning techniques. The ability to detect batteries with less expensive equipment and in a more efficient manner becomes increasingly important with the widespread propagation of battery powered IoT devices.

SUMMARY

[0005] In an embodiment, a harmonic radar system for detecting batteries includes a signal generator for generating one or more transmit radio frequency (RF) signals, one or more low-pass filters for removing harmonics from the transmit RF signals, a transmitting antenna for sending the transmit RF signals into an environment, a receiving antenna for receiving signals reflected or re-radiated by batteries in the environment in response to the transmit RF signals, one or more high-pass filters for filtering the received signals, and a spectrum analyzer for identifying a harmonic frequency of the transmit RF signals in the filtered signals.

[0006] A method of using a harmonic radar system for detecting batteries includes generating a transmit TX carrier frequency signal, transmitting the TX carrier frequency

signal into an environment including the electronic device, receiving a signal reflected or re-radiated by the battery in response to the TX carrier frequency signal, removing environmental and system-generated noise from received signal, and identifying a harmonic frequency of the TX carrier frequency signal in the received signal.

[0007] Throughout the disclosure, the terms energy storage device, battery cell and battery may be used interchangeably.

BRIEF DESCRIPTION OF THE FIGURES

[0008] FIG. 1A is a representative diagram of an equivalent metal-oxide-metal (MOM) circuit.

[0009] FIG. 1B is a representative diagram of an MOM junction found in battery cathodes.

[0010] FIG. 2 is a block diagram of a harmonic radar system 100 for detecting batteries, in embodiments.

[0011] FIG. 3 is a flowchart of a method of detecting a battery using the system of FIG. 2, in embodiments.

[0012] FIG. 4 is a graph of average received signal power, in embodiments.

[0013] FIGS. 5A-5C are graphs of harmonic response of reference signals, in embodiments.

[0014] FIGS. 6A-6F are graphs of harmonic response of standalone battery cells, in embodiments.

[0015] FIG. 7 is a graph illustrating frequency response at different frequencies, in embodiments.

DETAILED DESCRIPTION

[0016] Electronic devices that have computational and communication capabilities enabling them to collect and share information about their environment are becoming fully integrated into the daily lives of many users. Often referred to as “smart” devices, they are becoming a common fixture in many different types of environments—and yet their presence may not be readily apparent. Smart devices may include easy-to-spot smart assistants, however, they also include devices that are more difficult to visually detect due to their similarity in appearance to non-smart devices, such as smart light bulbs, smart door locks, or smart refrigerators. Other devices, such as surveillance cameras and microphones, may be purposefully located in difficult-to-observe locations to collect data without making their presence known.

[0017] Traditional radar may be used to detect devices in an environment by transmitting an RF signal toward a target. A portion of that signal is reflected or re-radiated from the outer portion or the encasing of the target. Assuming an otherwise empty environment, reflection indicates target detection and the time delay between TX (transmission) and RX (reception) is used to compute the range from the radar to the target. Traditional radar is linear; the set of frequencies reflected or re-radiated from the target is the same as frequencies transmitted, except for a slight difference imparted by relative motion between the target and the radar (the Doppler shift).

[0018] A major challenge in using a radar-like system to detect electronic devices in a cluttered environment such as a home or office is that the vast majority of objects in a typical environment generate a linear response so that the reflection of small electronics will be inter-mixed with reflections from walls, furniture, and people, among other obstacles. These linear responses arrive superimposed at the

receiver. At best, using radar for electronic device detection and identification requires heavy use of signal-processing techniques to declutter the return signal. In practice, even with strong algorithms it would be challenging to detect and identify the footprint of a small electronic target device amid all the clutter. Moreover, traditional radars detect targets by the reflection from their “enclosure” or outer shell, making it difficult to detect items that might be intentionally hidden (or lost and out of sight).

[0019] Harmonic radar is a technology that may be used to discover all types of smart devices in a home—even those that are powered off. It may work irrespective of the device’s communication protocols and may be able to detect malicious devices attempting to evade detection.

[0020] Harmonic radars work differently from linear radar. In particular, harmonic radar takes advantage of the nonlinear response of certain devices and substances to an RF signal. A harmonic radar system transmits a signal at a known frequency f_0 and listens for a return signal on a harmonic of the transmitted frequency (e.g., nf_0 , where n is a positive integer greater than one). When the transmitted signal encounters a nonlinear junction (which is common in electronic devices, see below), the nonlinear junction reflects or re-radiates the transmitted signal at harmonic frequencies related to the transmitted signal. When the transmitted signal encounters obstacles that lack a nonlinear junction, this reflection or re-radiation does not occur. This reflection or re-radiation characteristic may be leveraged by transmitting one or more frequencies while listening for reflections or re-radiations on the harmonics of the transmitted signals. The reflected or re-radiated power of the harmonic has an inverse relationship with its associated integer (lower values of n provide higher received power, higher values of n provide lower received power); descriptions herein use the first harmonic where $n=2$ (but other values for n could be used) and the RX frequency is $2f_0$.

[0021] Digital computation, even for simple devices like embedded systems, relies on semiconductors and other components that reflect or re-radiate RF signals nonlinearly. Harmonic radar systems are able to detect these devices and to identify them with high accuracy as described in Provisional Patent Application 63/522,236 filed Jun. 21, 2023, and titled “Harmonic Radar Scanner for Electronics,” incorporated herein by reference.

[0022] Harmonic radar can suffer from a problem: corrosion on targets can lead to false detection. Specifically, metal oxides such as rust also have a nonlinear RF behavior. This behavior, however, suggests an avenue for remotely detecting batteries. Commercially available battery cells contain metal oxides in the cathodes. In addition to electronic devices that reflect or re-radiate RF signals nonlinearly, metal oxides such as rust also have a nonlinear RF behavior. Since many types of commercially available batteries and battery cells contain metal oxides, this battery composition and its resulting nonlinear oxides are detectable by a harmonic radar.

[0023] Prior research into the nonlinear behavior of Lithium-Ion batteries has involved connecting batteries over a wire and leveraging the nonlinear behavior of the batteries’ chemical processes. For example, the “state-of-health” of the batteries may be estimated by applying a high-amplitude sinusoidal input signal through a wire connected directly to the battery system and measuring changes in the sinusoidal output voltage over time and estimate the loss capacity fade

due to loss of active material. Other research discusses the nonlinear behavior of Lithium-Ion batteries in the context of their electrochemical reactions during charge and discharge. Thus, the frequencies studied are limited to those associated with the chemical reactions.

[0024] The metal-oxide-metal junction created by corrosion of a metal can be modeled by the circuit shown in FIG. 1A. The junction between a battery cell’s cathode and the current collector follows a similar structure, as depicted in FIG. 1B; hence, a battery cell’s cathode-collector boundary is modeled with the equivalent circuit in FIG. 1A, with harmonic responses comparable to corroded metals. A harmonic radar may be used to remotely detect the presence of batteries using RF by leveraging the batteries’ physical structure.

[0025] In embodiments, a harmonic radar is used to detect many different types of batteries, such as Alkaline, NiMH, Li-ion, and Li-metal.

[0026] Various hardware devices are described herein, for example, signal generators, spectrum analyzers, filters and antennas. These devices are representative examples to illustrate principles disclosed herein but other devices and implementations may be used.

[0027] FIG. 2 is a block diagram of a harmonic radar system **100** for detecting batteries. The system can be generally divided into two blocks, transmitter block (TX) **102** and receiver block (RX) **104**. TX block **102** includes signal generator **106** which may generate signals with a range between approximately 50 MHz and 6 GHz, for example, although other frequencies may be used. In embodiments, signal generator may be a Signal Hound VSG60A, for example. Signal f_0 from signal generator **106** is received by low-pass filter **108**. Low-pass filter **108** may be a MiniCircuits SLP-2950+, which blocks harmonics produced by signal generator **106**.

[0028] In embodiments, TX block **102** includes power amplifier module **110** to increase the signal’s amplitude. Power amplifier module **110** may be an SBB5089+SZA2044 with a 40 dB gain, for example. In further embodiments, TX block **102** includes low pass reflection-less filter **112**, such as a MiniCircuits ZXLF-K312H+, and bandpass filter **114**, such as an HP **8431A**, to attenuate harmonics produced by power amplifier module **110** before the signal is transmitted by antenna **116**.

[0029] The RF signal transmitted by antenna **116** encounters target **118**. Signals reflected or re-radiated by target **118** are received at antenna **120** of RX block **104**. The relative positions of antennas **116** and **120** and target **118** are for purposes of illustration only.

[0030] In embodiments, the signal received at antenna **120** is sent to amplifier **122**, such as a TQP3M9037 LNA, which amplifies the received signal. One or more filters **124** and **126**, such as a MiniCircuits VHF-3800+high-pass filter and a HP **8435A** band-pass filter attenuate any scattering at the transmitted (fundamental) frequency. Spectrum analyzer **128**, such as a SignalHound BB60C, collects the received signal.

[0031] In embodiments, antennas **116** and **120** may be a LP0965 Log Periodic directional antenna for wireless transmission, and a BNC cable is used to connect the trigger channels of both TX block **102** and RX block **104** for synchronization. In embodiments, transmit antenna **116** and receive antenna **120** of FIG. 2 may be a single antenna

connected to a coupler. Both signal generator **106** and spectrum analyzer **128** are coupled to processing computer **130**.

[0032] FIG. 3 is a flowchart of a method **200** of detecting a battery using the system of FIG. 2. Method **200** includes steps **202**, **204**, **210**, **212**, **216** and **218**. In embodiments, method **200** also includes at least one of steps **206**, **208** or **214**. As discussed herein, the terms “capture” or “measurements” denote obtained data.

[0033] In step **202**, a TX carrier frequency signal is generated. In an example of step **202**, signal generator **106** is set to generate the TX carrier frequency f_0 at a power level of -20 dBm. The TX power level (-20 dBm) is selected so any unintended harmonic emissions are kept below the RF noise floor, as determined by previously acquired reference signals.

[0034] In step **204**, the TX carrier frequency signal is filtered. In an example of step **204**, low-pass reflection-less filter **108** is used to remove harmonics.

[0035] In step **206**, the filtered TX carrier frequency signal is amplified. In an example of step **206**, the filtered TX carrier frequency signal is amplified using power amplifier module **110**.

[0036] In step **208**, the amplified signal is filtered. In an example of step **208**, the amplified TX carrier frequency signal is filtered by one or more filters such as filter **112** or filter **114** to remove harmonics produced through amplification.

[0037] In step **210**, the TX carrier frequency signal is emitted towards a target. In an example of step **210**, the TX carrier frequency signal is transmitted by antenna **116** into an environment including a battery. Signal generator **106** is set to emit a 0.6 ms Continuous Wave (CW) pulse. The trigger channel is pulled “high” until transmission ends, and spectrum analyzer **128** is set to capture twice as long (1.2 ms) to avoid missing the pulse. The length of the transmitted pulse may be selected experimentally to minimize the acquisition time and raw data size.

[0038] In step **212**, a signal reflected or re-radiated by the battery in response to the TX carrier frequency signal is received. In an example of step **212**, the RX carrier frequency is set to $2 f_0$ and the maximum receive power level to 0 dBm.

[0039] In step **214**, the received signal is amplified. In an example of step **214**, the received signal is amplified by amplifier **122**.

[0040] In step **216**, the amplified signal is filtered. In an example of step **216**, One or more filters **124** and **126**, are used to remove environmental and system-generated noise from received signal.

[0041] In step **218**, the received signal reflected or re-radiated by the target is analyzed. In an example of step **218**, a flat-top window is applied to RX-captured IQ data and used to calculate a Discrete Fourier Transform (DFT).

[0042] In embodiments, the signal strengths for all harmonic responses are determined by averaging the power spectrum over 10 “captures.”

[0043] In data processing, the DFT window is the most important design parameter. Harmonic radar detection is heavily dependent on changes of received power, so in embodiments, a flat-top window is applied, to produce more accurate amplitude estimates, before computing the transform with the DFT algorithm. Although the received peak power is not dependent on the pulse length, the power

estimated from the DFT is affected by the DFT window length. Using measurements taken on a very responsive nonlinear target, such as an iPhone **13** Pro Max, different window sizes may be evaluated. As shown in FIG. 4, the power estimate plateaus at a 4000 -point window; thus, the closest power of two (i.e., 4096 points) may be chosen for the DFT window size. The DFT algorithm takes advantage of symmetries that result from windows with a size that is a power of 2 .

[0044] For peak detection, the maximum value in a bin is chosen. This method is simple, fast, and accurate. This method may result in an incorrect frequency bin selection (i.e., the maximum peak may not always be at the same bin); since the frequency is known beforehand, it is only necessary to look at the neighboring bins within the spectrum analyzer and signal generator errors. In embodiments disclosed herein spectrum analyzer **128** and signal generator **106** both have a reported error of 2.0 ppm, which results in around 7 KHz of uncertainty from the set frequencies: 2.3 GHZ (TX) and 4.6 GHZ (RX). In the worst-case scenario, with maximum uncertainty in both generator and analyzer, there can be 14 KHz uncertainty in the DFT center frequency; with the selected DFT size (4096), the frequency resolution is 9.8 KHz; hence, examination of only three bins is needed to find the maximum peak, that of the center frequency (bin 0) as well as the two closest neighbors (bin -1 and bin 1).

[0045] In embodiments, $f_0=2.3$ GHZ. In general, the harmonic response of consumer electronics is maximal in the region around 2.4 GHZ due to the operation frequency range of the target devices. As disclosed herein, a slightly different frequency from $f_0=2.3$ GHZ may be used to avoid any potential Wi-Fi or Bluetooth interference.

[0046] Device detection mechanisms based on harmonic radar technology are dependent on differences between the background environment (e.g., no target device present) and the signal received from a target device. As used in this representative example, ‘detection’ means that observed response was at least 3 dBm higher (i.e., double the power) than the background environment. This threshold represents the worst-case detection scenario.

[0047] FIGS. 5A-5C are graphs of harmonic response of reference signals, in embodiments and summarize the measured average RX power for the reference signals when testing non-battery targets. To differentiate batteries from other objects, three non-battery target configurations were evaluated: a background response with no objects present, a cardboard box representing a non-reflective object, and an aluminum foil coated box representing a highly reflective object. This test served to quantify the environmental and system generated noise without a target device. Because these reference items do not contain nonlinear junctions, we expected them to display no nonlinear response. Results are shown in FIGS. 5A-5C for f_0 is set to 2.3 GHZ.

[0048] The noise floor of the system is estimated to be -87.6 ± 1.7 dBm as shown by the background capture in FIG. 5A. Additionally, the cardboard and aluminum responses, FIGS. 5B and 5C, respectively, serve as a reliability indicator for the chosen frequency and power settings as well as the correct operation of the radar overall. One of the major sources of error for harmonic radars is the reflection of “leaked” energy at $2f_0$ generated by the nonlinear components in the circuit. The fact that both references are within the expected deviation from the average background (e.g.,

they did not have a harmonic response) confirmed the harmonic radar was working as intended.

[0049] FIGS. 6A-6F are graphs of harmonic response of standalone battery cells and show that the harmonic radar easily detected the batteries using the system of FIG. 2 with a 3 dBm threshold, except for the CR2032 coin cell. This may have been due to the battery's small size. A lower threshold (less than 3 dBm) could have been used to detect the coin cell. The results are summarized in Table 1 below. The larger the battery (e.g., AA vs. AAA), the higher the average response. For example, the NiMH AA battery had an average response of -80.0 dBm as shown in FIG. 6D, but the AAA form factor only had an average response of -82.1 dBm as shown in FIG. 6A. Due to decibel's nonlinear scale, 3 dBm is a half power point, suggesting the difference of 2.1 dBm may be significant.

TABLE 1

Battery Type	Response (dBm)	Difference
Background	-87.6	0.0
NiMH AAA	-82.1	5.5
Alkaline AAA	-80.2	7.4
CR2032	-86.1	1.5
NiMH AA	-80.0	7.6
Alkaline AA	-78.2	9.4
Li-Ion 18650	-76.6	11.0
Nexus S Li-Ion	-80.6	7.0

[0050] Although representative frequencies have been discussed, this is for purposes of illustration and other frequencies may be used by harmonic radar systems **100**. For example, FIG. 7 depicts the results using the system of FIG. 2 with a range of f_0 values, for three batteries (Alkaline AA, NiMH AA, Li-Ion 18650). The batteries do not show much difference in response across the tested frequencies. Small differences in power can be observed throughout the spectrum; such differences, however, cannot be used to distinguish battery types and form factors since they can be easily counteracted by changing the relative distance between battery cells and the radar's antennas

[0051] Embodiments discussed herein include harmonic radar systems capable of detecting the presence of battery cells. This may become handy in situations where batteries, on their own, represent a security threat-such as checked bags containing Li-Ion batteries in airplanes, or situations where batteries might need to be detected amid other "linear clutter" such as in recycling plants.

[0052] Changes may be made in the above methods and systems without departing from the scope hereof. For example, although a range of frequencies f_0 has been discussed as determined by the capabilities of the harmonic radar hardware. Although these frequencies seem suitable for the detection of consumer-grade electronics, other frequencies may be used. Further, increased maximum detection ranges may be possible. Combined device and battery systems: Nonlinear junctions found in electronic devices (i.e., transistors) are known to have a measurable harmonic response. Although our results show that batteries, by themselves, produce a measurable harmonic response, we have not tested the ability of the system to detect batteries installed in electronics. The presence of nonlinear components in electronics may mask or amplify a target's harmonic response.

[0053] It should thus be noted that the matter contained in the above description or shown in the accompanying drawings should be interpreted as illustrative and not in a limiting sense. The following claims are intended to cover all generic and specific features described herein, as well as all statements of the scope of the present method and system, which, as a matter of language, might be said to fall therebetween.

What is claimed is:

1. A harmonic radar system for detecting a battery, comprising:

- a signal generator for generating one or more transmit radio frequency (RF) signals;
- one or more low-pass filters for removing harmonics from the transmit RF signals;
- a transmitting antenna for sending the transmit RF signals into an environment;
- a receiving antenna for receiving signals reflected or re-radiated by the battery in the environment in response to the transmit RF signals;
- one or more high-pass filters for filtering the received signals; and
- a spectrum analyzer for identifying a harmonic frequency of the transmit RF signals in the filtered signals.

2. The harmonic radar system of claim 1, wherein at least one of the low-pass filters is a reflection-less filter.

3. The harmonic radar system of claim 1, comprising a transmitting amplifier coupled between the signal generator and the transmitting antenna.

4. The harmonic radar system of claim 1, comprising a receiving amplifier.

5. The harmonic radar system of claim 1, wherein the signal generator generates signals between approximately 50 MHz and 6 GHz.

6. The harmonic radar system of claim 1, wherein a center frequency of one or more transmit RF signals is $f_0=2.3$ GHz.

7. The harmonic radar system of claim 1, further comprising a processing computer coupled to the signal generator and spectrum analyzer.

8. A method of using a harmonic radar system for detecting a battery, comprising:

- generating a transmit TX carrier frequency signal;
- filtering the TX carrier frequency signal to remove harmonics;
- transmitting the TX carrier frequency signal into an environment including the battery receiving a signal reflected or re-radiated by the battery in response to the TX carrier frequency signal;
- removing environmental and system-generated noise from received signal; and
- identifying a harmonic frequency of the TX carrier frequency signal in the received signal.

9. The method of claim 8, wherein the TX carrier frequency signal comprises $f_0=2.3$ GHz.

10. The method of claim 8, wherein a receive (RX) carrier frequency is set to $2f_0$ GHz.

11. The method of claim 8, wherein filtering the TX carrier frequency signal to remove harmonics includes using a low-pass reflection-less filter.

12. The method of claim 11, further comprising amplifying the filtered TX carrier frequency signal.

13. The method of claim 12, further comprising filtering the amplified TX carrier frequency signal to remove harmonics produced through amplification.

14. The method of claim **8**, wherein removing environmental and system-generated noise from received signal further comprises filtering the received signal.

15. The method of claim **14**, further comprising amplifying the received signal before removing environmental and system-generated noise.

* * * * *