Laser optoacoustic effect as a possible cause of some incidents attributed to Havana syndrome

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Abstract

Havana syndrome is a cluster of distressing symptoms (including hearing problems, dizziness, nausea, and headaches) first reported in 2016 among employees of the US and Canadian embassies in Havana, Cuba, and subsequently observed in individuals in other countries. The most frequently cited potential causes of the syndrome have been exposure to microwave radiation, insecticides, and psychogenic factors.

The analysis presented in this paper demonstrates that, in addition to the possible scenario of organophosphate insecticide poisoning (section 3.2) and a resulting psychogenic response (section 3.3), a microwave mechanism for Havana syndrome incidents (the Frey effect) is highly improbable (sections 5–7), a conclusion supported by previous research.

The most likely physical cause of these incidents is the laser-induced optoacoustic effect (sections 6–7). Laser-directed energy technologies are considerably more compact, user-friendly, effective, and covert than alternative mechanisms, even when deployed against individuals in confined spaces (section 6.2).

The accessibility of laser technologies means they could be employed by a range of state and non-state actors, not solely by Russian intelligence services, which have been most frequently implicated in investigations (section 6).

It is recommended that collective and individual diagnostic methods for potential exposures to at-risk personnel be enhanced by utilizing sensors operating in the infrared, ultraviolet, and visible light spectrums, in addition to the microwave range (sections 6.3.2, 7).

/1/ Introduction

The "Havana syndrome" is a complex and multifaceted phenomenon. It includes medical, technical, psychological, political aspects, as well as the sphere of interaction of government officials and journalists with scientists and engineers - narrow specialists in various topics. The present study focuses primarily on the scientific and technical dimensions of this issue. The history of the Havana syndrome is described in detail in the materials of several large-scale investigations commissioned by American government agencies, for example, [JASON, 2021; IC Experts Panel on AHIs, 2022; National Intelligence Council, 2023a, 2023b], in major investigations of leading American media, for example, [Golden & Rotella, 2018; Broad, 2018; Entous, 2021], the investigation of the project The Insider, CBS and Der Spiegel [Dobrokhotov et al., 2024; Weiss et al., 2024, Croxton, 2024], and on English Wikipedia [Wikipedia. Havana syndrome, 2017-2024].

[1] https://scholar.google.com/citations?hl=ru&user=_O5_VEIAAAAJ&view_op=list_works&sortby=pubdate , *kostinsky@gmail.com*

In this paper, in addition to the microwave auditory effect, we will consider in detail the laser optoacoustic effect, which, as far as we know from open sources, was not discussed in the study of the Havana syndrome incidents. The laser optoacoustic effect is easy to implement technologically and use for remotely creating, arbitrarily, large pressures in the human cranium, up to the creation of shock waves. For this, we will consider the physics of the optoacoustic effect, a special case of which is the microwave auditory effect (the Frey effect), which was considered in some investigations to be the most likely mechanism of influence on US government employees. Optoacoustics, photoacoustics and thermoacoustics are exact synonyms of each other, which we will discuss in detail in Section 5.4.

The main hypothesis of this paper is the possible use of laser technologies to create some incidents related to the Havana syndrome, since laser systems are more effective than microwave systems in any impact on "targets", including even "targets" in closed spaces. Therefore, the initiators of some incidents (if they occurred) may be different state and/or non-state actors, and not only the Russian special services most often assumed in investigations.

/2/ Medical aspect

Asadi-Pooya analyzed the scientific databases MEDLINE, Scopus and Ovid, as well as Google Scholar for the period from 2016 to September 24, 2021 and found 120 scientific publications that mentioned Havana syndrome. As a result, he identified 5 original studies and 18 detailed scientific discussions (comments) on the basis of which this picture of events was obtained [Asadi-Pooya, 2023].

The first cases of Havana syndrome were reported in 2016 among several employees of the US and Canadian embassies in Havana, the capital of Cuba, and their family members. Hence the name “Havana syndrome”. Since then, up until the present day, more than a thousand people have reported similar symptoms, which have been recorded in China, Vietnam, India, the US, Austria, Bulgaria, France, Georgia, Poland, Serbia, Switzerland, the UK, Australia, Colombia, Kyrgyzstan, Syria, Taiwan, and Uzbekistan [Regenstein, 2024]. Recently, retroactive evidence has also emerged of possible similar events in Frankfurt, Germany in 2014 [Dobrokhotov et al., 2024; Weiss et al., 2024].

Havana syndrome can be defined as a set of painful, and in 134 cases, traumatic conditions of people associated mainly with a strong impact on the human auditory and visual apparatus: " Havana syndrome is a nonspecific neurological illness with an unidentified causative factor(s), an acute phase of auditory-vestibular symptoms and a chronic phase of nonspecific neurobehavioral symptoms." [Asadi-Pooya, 2023].

Research has identified two stages: acute initial syndromes and subsequent chronic symptoms of Havana syndrome.

/2.1/ Acute symptoms of Havana syndrome

Acute symptoms of Havana syndrome have been documented in three scientific studies [Swanson et al., 2018; Hoffer et al., 2018; Friedman et al. 2019a, 2019b] and an investigation by the US National Academies of Sciences, Engineering, and Medicine (NASEM) [NASEM, 2020]): sudden sensation of a loud or shrill sound, screeching, chirping, clicking (in 90% of cases); visual disturbances such as: blurred vision and excessive sensitivity to light (66%); a feeling of strong pressure or vibration in the head (more than 50%); ear pain or general headache (more than 50%); cognitive problems such as: forgetfulness, poor concentration (more than 50%), ringing in the ears (30%), hearing loss (30%); dizziness, unsteady gait (25%).

At least 2 of these symptoms were simultaneously recorded in 96% of patients, and at least 3 symptoms were simultaneously noted in 56% of patients [Hoffer et al., 2018]. Many of the victims reported immediate onset of neurological symptoms related to the targeted impact on them (emphasis in the entire text of the article is ours, in other cases this will be specified).

/2.2/ Chronic symptoms of Havana syndrome

Chronic symptoms of Havana syndrome (formulated according to [Swanson et al., 2018] and the investigation [NASEM, 2020]): problems with balance and vestibular apparatus - dizziness (78%), nausea (33%); problems with vision and oculomotor problems - photosensitivity (62%), eye strain (52%); problems with hearing - sensitivity to sounds (67%), tinnitus (57%), hearing loss (43%); cognitive problems - impaired concentration (44%), memory impairment (55%); neurobehavioral difficulties - irritability (67%), nervousness (57%), sadness (24%); insomnia (85%); fatigue (48%); headache (48%).

The researchers emphasized that all of their data did not have a corresponding control group unaffected by Havana syndrome for comparison, and their findings should be interpreted with caution. The chronic symptoms listed above cannot necessarily be interpreted as “chronic” because the chronic phase has not yet been defined and the duration of symptoms is not yet clear [NASEM, 2020; Asadi-Pooya, 2023].

Critiques of the early studies [Swanson et al., 2018; Hampton, Swanson, & Smith, 2018; Hoffer et al., 2018] that shaped the Havana syndrome phenomenon itself were swift and brutal compared to the styles of normal scientific debate. Della Sala and Cubelli published a commentary, “Alleged ‘sonic attack’ supported by poor neuropsychology” [Della Sala and Cubelli, 2018]. They argued, “The JAMA article [Swanson et al., 2018] represents a case of poor neuropsychology; clinically inappropriate and methodologically improper. Only six of the 21 people considered in the study completed the battery of 37 tests. <…> No demographic data are provided, nor are the raw scores suppliedeonly percentiles are given.” <...> “In conclusion, there is no evidence that the people assessed present with any cognitive deficit (to be linked or not with their stay in Cuba). Subjective cognitive symptoms cannot be supported by the reported data. There is no “new syndrome” to contemplate. Hence, the search for its cause is moot.” [Della Sala and Cubelli, 2018]. JAMA is the flagship scientific Journal of the American Medical Association (JAMA), which published the first results of medical examinations of those complaining of symptoms of Havana syndrome.

The Cortex Editorial Board, in an editorial titled “Responsibility of neuropsychologists: The case of the “sonic attack’”, states: “This Editorial is concerned with the higher level issue of how such self-contradictory statements could come to be published at all, let alone in a journal of JAMA's reputation and stature. Allowing such confused and conflicting explanations of methodology and analysis to pass unchallenged is a slippery path for science, and dangerous for society at large Reporting cognitive impairments, unsupported by rigorous evidence, invites media coverage that may lead to widespread public misconception about the nature of this phenomenon. <...> Given this lamentable state of affairs, the authors of the JAMA report should now either publish an official Erratum, to explain their actual methods clearly and unambiguously, or they should retract the original paper.” [Cortex Editorial Board, 2018]

/3/ Possible causes (etiology) of Havana syndrome (first versions)

Three main hypotheses have been proposed:

- Hypothesis of exposure to pulsed microwave radiation.
- Neurotoxin hypothesis.
- Psychogenic hypothesis.

/3.1/ Pulsed Microwave Radiation Hypothesis

In a major report, experts from the National Academies of Sciences, Engineering, and Medicine (NASEM) concluded that "the most plausible mechanism for Havana syndrome is a directed, pulsed radio frequency (RF) source." NASEM also emphasized that it is likely that some cases and differences between cases are explained by more than one exposure [NASEM, 2020]. In the NASEM report, a pulsed RF source was defined as a powerful pulsed microwave source that can, when irradiated, produce a "microwave auditory effect" in the human head, also known as the Frey effect. We discuss the possible role of the Frey effect in detail in Sections 5 and 6.

The main arguments in favor of the Frey effect were: the ability of microwave radiation to penetrate glass, brick, wood (dielectrics) with reasonable losses, since many of the supposed effects occurred indoors; and the creation of sufficiently strong sound waves inside the cranium, which could, by repeatedly reflecting inside the cranium, affect the auditory and vestibular apparatus, the optic nerves, and other organs. Patients simultaneously recorded several acute symptoms at the beginning of the effect (section 2).

The Frey effect was apparently first proposed as a cause of Havana syndrome by James C. Lin [Lin, 2018]. He was also a consultant to NASEM, and his presentation to the panel may have influenced NASEM's conclusions [Lin, 2021a].

The main alternative scientific hypotheses were the psychogenic hypothesis and the hypothesis of the effects of neurotoxins.

/3.2/ Neurotoxin Hypothesis (Exposure to Embassy and Diplomats’ Residences via Insecticide Spraying)

At the request of Global Affairs Canada, a team of Canadian scientists conducted detailed studies of 26 Canadian diplomats using a control group “not exposed in Havana.” They included detailed interviews with the diplomats, review of their medical histories and mandatory pre-deployment medical examinations, extensive physical examinations, mass spectrometry, blood tests, brain imaging (magnetoencephalography and magnetic resonance imaging), and cognitive, auditory, and vestibular function. This was a detailed and comprehensive study of the diplomats who reported symptoms in Havana. They concluded that Havana syndrome in Cuba is the result of acquired neurotoxicity (overexposure to cholinesterase inhibitors). The group, based on a large data corpus, hypothesized that the diseases were caused by overexposure of humans to mosquito repellents (organophosphate insecticides) [Friedman et al., 2019a, 2019b].

The insecticidal hypothesis has strong support, given the extensive documented efforts of the Cuban government to combat the Zika virus epidemic in 2016. They deployed over 9,000 soldiers to spray mosquito repellents against the virus-carrying mosquitoes in stores, restaurants, stalls, gardens, and homes [Reardon, 2016]. The authors of the Canadian study also cite official records from the Canadian embassy in Havana that show a sharp increase in mosquito repellent spraying around and inside the homes of embassy staff beginning in January 2017, in parallel with reported illnesses [Friedman et al., 2019a, 2019b].

/3.3/ Psychogenic Hypothesis

The third hypothesis was put forward by Robert Bartholomew [Bartholomew, 2017]: "Politics, scapegoating and mass psychogenic illness: claims of an 'acoustical attack' in Cuba are unsound." Later, Bartholomew and Baloh consistently developed this hypothesis [Bartholomew and Baloh, 2020; Baloh and Bartholomew, 2020; Bartholomew and Baloh, 2024]. Their main conclusion was: "Based on the weight of evidence, we believe that the most likely explanation for the recent outbreak of mysterious symptoms in Cuba and elsewhere is mass psychogenic illness triggered by rumours of the development of a new and enigmatic sonic device." [Bartholomew and Baloh, 2020].

The critical part of their commentary was based on the characterization of the first detailed medical (neuropsychological) study of Havana syndrome, led by Swanson and Smith [Swanson et al., 2018] (see also Section 2.3). It was on the basis of the research of Swanson and Smith and their colleagues from the University of Pennsylvania [Swanson et al., 2018] that officials in the Donald Trump (then new US President) administration concluded that there had been an attack on embassy staff in Havana, and then greatly reduced the number of US diplomats in Cuba and expelled 17 Cuban diplomats from the US [Della Sala and Cubelli, 2018].

According to Bartholomew and Baloh, in Cuba, US embassy staff shared a common work environment in an atmosphere of psychosocial stress, generated by a long history of antagonism with Cuba's intelligence services. After the symptoms were suspected to be due to "sonic weapons," US diplomats traveling to Cuba were confidentially warned before their deployment that they might face a mysterious threat that was causing US diplomatic personnel to fall ill, some with long-term symptoms [Oppmann & Labott, 2017].

Bartholomew and Baloh draw a parallel with the concerns of people living near wind turbines, citing the paper [Crichton et al., 2014]. There is no connection between illnesses in people living near wind turbines and the sound produced by their blades, as this sound is too weak to cause harm. However, some people have reported getting sick because of the unbearable noise of wind turbines. That is, their painful sensations are definitely psychogenic in origin.

According to Bartholomew and Baloh, the same pattern of shaping expectations of painful symptoms was implemented in the case of American diplomats. Before they were supposed to take up their posts, new embassy employees were not only informed that they could become the next "targets" of attackers, but were also prepared for "attacks" by letting them listen to suspicious sharp sounds recorded earlier by American employees in Havana. Some of these recordings were later identified by Cuban scientists as the mating calls of the Indian short-tailed cricket (Anurogryllus celerinictus) and the Jamaican field cricket (Gryllus assimilis) [Stone, 2017]. American scientists independently confirmed the findings of their Cuban colleagues regarding crickets, which produced sounds with a maximum amplitude of 74 dB, while hearing impairment requires a volume $4x10^5$ times greater (130 dB) [Stubbs & Montealegre-Z (2019).

The psychogenic hypothesis for the causes of Havana syndrome incidents has proven to be the most successful, explaining at least 90% of the more than a thousand health complaints from people in different parts of the world.

/4/ Testing the psychogenic and ultrasound hypotheses as a result of government investigations

Complaints from employees of the US embassy in Havana, and later in other countries, gave rise to, firstly, an FBI investigation in the wake of the events. Secondly, numerous consultations of government agencies with scientists and engineers of various specialties were held. Thirdly, government organizations commissioned several original scientific studies, designed as scientific articles, and detailed investigations were launched, which were conducted by specially created commissions consisting of experts (expert panels).

/4.1/ Golden and Rotella's Investigation

An important investigation for understanding the causes of the Havana syndrome was conducted by ProPublica journalists Tim Golden and Sebastian Rotella [Golden & Rotella, 2018]. They conducted more than 30 interviews with participants in the events in Cuba.

Their investigation revealed that “patient zero” (the first person to report the illness) believed that “In late December (2016 — A.K), he said, he had been struck by a strange, disturbing phenomenon — a powerful beam of high-pitched sound that seemed to be pointed right at him.” Based on this, he reported to his superiors and traveled to Miami, where medical specialists discovered a number of problems, including partial hearing loss. Upon returning to Havana, “patient zero” began warning his colleagues and acquaintances about the danger.

One of the diplomats told reporters that he and his wife, like their neighbors, heard, often in the evening, very loud sounds that they took for the chirping of cicadas. They did not attach any special significance to this and did not feel any signs of illness or injury. But when they met, “patient zero” convinced them of serious danger and played a recording of the “noise” that was the culprit of the problems, which sounded to the diplomat very similar to what he took for the chirping of cicadas. Despite the absence of complaints and injuries, the diplomat and his wife, under the influence of the information from “patient zero”, flew to Miami along with 22 other Americans and eight Canadians and they were also diagnosed with a wide range of symptoms similar to concussion.

The first four patients, including “patient zero,” were likely CIA officers under diplomatic cover, a very tightly knit professional and emotional group who were in the greatest danger. Two more CIA officers later joined the victims [Golden & Rotella, 2018].

Thus, the onset of Havana syndrome in most cases is consistent with the psychogenic hypothesis. The "group zero" of 4-6 closely related individuals received information from the " patient zero" about the existence of a mysterious "high-frequency sound beam", the effects of which are very serious (including hearing loss).

It is also possible that some of the American embassy staff, including CIA employees, received real injuries during this period, but not due to the “mysterious rays,” but due to excessive spraying of insecticides, like the Canadian diplomats [Friedman et al., 2019a, 2019b]. Therefore, “patient zero” and some of the participants in the “group zero” could have received real injuries, and doctors in the first studies recorded real symptoms of the disease.

/4.2 / Cuban Investigations

From the very beginning of the diplomatic conflict between the US, Canada and Cuba over possible "sonic attacks" on diplomats, the Cuban authorities sharply and unequivocally denied their involvement in the incidents. At that time, the Cubans were feeling out a new economically flexible path of development, closer to the Chinese or Vietnamese experience, and for this they needed American investments in the economy.

The Cubans organized their own large investigation [Stone, 2017]. Cuban media reported that about 2,000 people participated in the investigation. Unfortunately, the strong dependence of Cuban scientists on the Cuban government diminished the significance of their arguments in the eyes of independent observers.

/4.3/ The FBI's First Investigation and the Ultrasound Hypothesis

The FBI's investigative team, which included members of the Miami-based Latin America Unit, visited Cuba four times since May, and the Cubans provided them with full cooperation [Lederman & Lee, 2018; US Senate Foreign Relations Committee Hearing, 2018] (section 4.2).

FBI investigators, following their own investigation, agreed with the preliminary findings of a classified report by the Operational Technology Division of the Science and Technology Branch of the FBI, which concluded that the Americans' symptoms were not caused by any sonic device [Golden & Rotella, 2018]. Not only does an ultrasonic beam lose almost all of its energy when passing through walls and glass, but it also fades in the air over distances of several meters, meaning it can only be used to cause injury at close range to a victim who is not obstructed by any solid obstacle [Kikoin, 1976, p. 78].

The investigators' conclusions were also based on the opinion of Allen Sanborn, a biologist at Barry University in Miami Shores (Florida), an expert on cicadas, crickets, and grasshoppers. Sanborn confirmed that cicadas can produce very loud sounds, but they could not cause injury. He estimated that the Cuban cicada can produce a very loud sound of up to 95 dB at a distance of about 50 cm from the ear [Golden & Rotella, 2018]. The threshold for pain from sound occurs at 120 dB, which is 18 times greater than 95 dB, and ear injury can be caused by sound at a sound pressure of 130-140 dB, which is 56-178 times greater than 95 dB [Physical Encyclopedia, 1994, p. 87].

/4.4/ The hypothesis about the involvement of Russian special services in the incidents in Havana

The hypothesis about the involvement of Russian special services in the Havana syndrome arose almost immediately after the hypothesis about a strong acoustic impact was discarded, and the microwave hypothesis became the most probable.

On January 9, 2018, a Senate hearing entitled “Attacks on U.S. Diplomats in Cuba: Response and Oversight” [US Senate Committee on Foreign Relations, 2018] was held. During the hearings, the hypothesis of Russian involvement was raised several times. On the other hand, ProPublica journalists, analyzing the information received by that time, wrote about the uncertainty of many officials about the involvement of Russian intelligence services in the Havana syndrome.

/5/ Analysis of the microwave hypothesis to explain incidents attributed to the Havana syndrome

We are not considering the fundamental possibility of the Frey effect to create a sensation of sound in the human cranium. The very "hearing" of microwaves does not create medical problems. At least a thousand people in the 1940s-1970s recorded this effect and they had not only no injuries, but also no painful conditions (section 5.2). We are considering such high levels of microwave radiation power density in the human head area that lead to either painful sensations or injuries. And, accordingly, we are discussing such microwave systems that can provide microwave power densities above the pain (traumatic) threshold at distances of at least 30-100 meters from the transmitting devices.

In order for specific “perpetrators” (attackers) to use electromagnetic radiation to create acute pain or injury in people (“targets” of the impact), several conditions must be met:

(1*) The power density of electromagnetic radiation in the area of the "target's" head must exceed the threshold values for creating a painful or traumatic sensation. Therefore, the electromagnetic energy generation system must create a beam of such power, duration and divergence that, despite the losses in beam transportation along the path from the emitter to the target, the radiation density in the area of the head exceeds these threshold values.

(2*) The source of electromagnetic radiation, the energy transport system to the emitter, and the passage of the beam to the target must be camouflaged, and in the event of detection, the system must be quickly dismantled and camouflaged or destroyed (it is desirable that it be mobile).

(3*) The entire target irradiation system must be so reliable, simple and convenient in transportation, installation, control and dismantling that it could be used under conditions of many restrictions and stress by "performers" without special technical abilities, which are mid-level employees of special services and criminal structures. They can (and must) act only according to a clear algorithm (instructions) and are not supposed (are excluded) to solve creative technical problems in case of problems during installation or abnormal operation of equipment (failure, breakdown), in the process of performing the task.

/5.1/ Effect of microwave radiation on people due to thermal heating

Microwave radiation is electromagnetic waves with a radiation frequency of 0.3-300 GHz and wavelengths from 1 meter to 1 mm. The energy of a microwave photon is 10^4-10^5 times less than the energy of photons of visible light and ultraviolet. In the microwave range of electromagnetic waves, rotational energy levels of a water molecule (H_2O) effectively absorb radiation. For $\sim 10^{-12}\ s$, excited rotational levels of H_2O give up excess energy to the surrounding colder molecules and the heating of the entire irradiated area occurs quite uniformly. Microwave radiation is classified as non-ionizing radiation, that is, radiation whose photons cannot detach an electron from an atom or molecule (ionization). The main effect of microwave radiation on any biological tissue is heating.

Microwave radiation is also a wave, which consists of alternating electric and magnetic fields. According to Maxwell's equations, the power density of a plane electromagnetic wave $P\left[\frac{W}{m^2}\right]$ determines the mean square electric field $\tilde{E}\ \left[\frac{V}{m}\right]$ according to the formula [Purcell, 2011, p.340; Benford et al., 2016, p.441]:

$$P\left[\frac{W}{cm^2}\right] \cong \frac{\left(\tilde{E}\left[\frac{V}{cm}\right]\right)^2}{377};\ \tilde{E}\ \left[\frac{V}{cm}\right] \cong 19.4\sqrt{P\left[\frac{W}{cm^2}\right]};\ \tilde{E}\ \left[\frac{V}{m}\right] \cong 19.4\sqrt{P\left[\frac{W}{m^2}\right]} \qquad (1).$$

This formula is applicable to all ranges of electromagnetic waves: ultraviolet, visible, infrared, microwave, radio. In square brackets in the formulas, we write units of measurement.

If electromagnetic fields reach high values, they can cause malfunctions of electronic devices (more than 250 kW/m^2, more than 10 kV/m) [JASON, 2021, pp. 65-67]. Even stronger electric fields create an electrical breakdown on the surface of electronic boards, which disables them. Also, a breakdown in the electromagnetic wave field occurs on sharp, thin conductive objects (more than 20 MW/m^2, more than 86 kV/m). Extremely strong electric fields create a discharge in the atmospheric air (more than 23 GW/m^2, more than 3.2 MV/m). Electrical breakdown (discharge) on the surface or air breakdown occurs with an avalanche-like multiplication of electrons, so very strong electric fields lead to ionization, that is, electromagnetic waves of very high-power density ionize gas near the surface or in free space. But even the microwave radiation that creates the discharge is not ionizing radiation, since vacuum ultraviolet, X-ray and gamma radiation are considered ionizing radiation, where each individual photon of the electromagnetic field can ionize atoms and molecules of the medium.

/5.2/ Effects of microwave radiation on humans due to the microwave auditory effect (Frey effect)

The microwave auditory effect is the second, after the thermal effect, reliably established physical mechanism of the influence of microwaves on living organisms. The first reported possible auditory perception of microwave pulses was in 1956 by employees of the Airborne Instruments Laboratory (AIL) [AIL, 1956; Lin, 2021b]. These reports were documented by AIL engineers in a technical report, in which several people reported hearing microwaves. They were later interviewed and field tested by Alan Frey [Frey, 1961; Lin, 2021b].

Microwave auditory effect was defined as the auditory perception of microwave radiation or simply hearing microwaves. After the first articles by Alan Frey, several series of experiments were conducted with volunteers. During the experiments, if the volunteers “heard” a sound, they pressed a button and an indicator lit up on the experimenter’s side. Horn antennas, from which microwave radiation emanated, were installed at distances of 10-50 centimeters from the backs of the volunteers’ heads (Figure 1) [Frey & Messenger, 1973; Guy et al., 1973; Cain & Rissmann, 1978].

The results of these controlled laboratory studies confirmed that humans clearly hear sound when their heads are exposed to microwave pulses of frequencies ranging from 0.2 to 6.5 GHz with peak power densities in the range of 2 to 40 kW/m^2 and pulse durations ranging from 1 to 100 μs.

Field (near active high-power radars) and laboratory experiments were conducted on human volunteers. The total number of people who reported microwave auditory effects was at least a thousand, and most likely several times more. Each of them was irradiated with microwave energy for tens of minutes with a power density in the range of 2–40 kW/m^2 [Lin, 2021b], which is 40–800 times greater than the maximum permissible level for industrial premises currently accepted [IEEE, 2019; ICNIRP, 2020]. At the same time, no noticeable number of diseases of the volunteers were recorded.

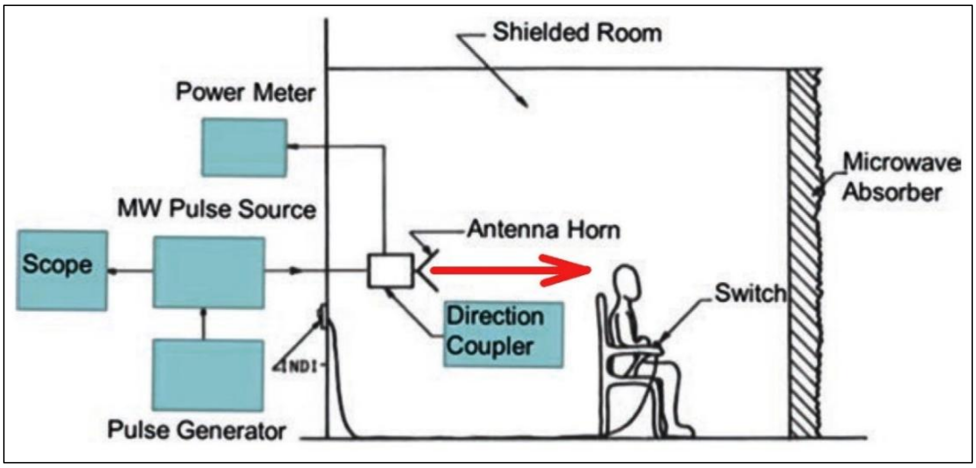

Figure 1. Sketch of the experimental setup for studying the microwave auditory effect (Frey effect) induced by microwave pulses in humans. Adapted from [Lin, 2021b].

/5.3/ Hearing threshold, pain threshold and injury threshold of the microwave auditory effect

The Frey effect not only did not cause illness, but was not felt by hundreds of volunteers as an unpleasant phenomenon — these were simply unusual sounds. Therefore, the Frey effect, as such, is not a damaging factor at low and medium levels of sound perceptible to humans, which was detected during the operation of radars and then reproduced in field and laboratory experiments [Lin, 2021b]. In connection with James Lin's microwave hypothesis [Lin, 2018] (section 3.1), the question arises: what energy densities can cause pain and injury similar to those attributed to the Havana syndrome?

Experiments on causing pain and injury to people due to the microwave hearing effect, as far as we can judge from open publications, have not been conducted. Therefore, James Lin proposed a method for determining the pain threshold based on an analogy with the usual sound pain threshold of the ear, which occurs at a sound pressure of about 120 dB (in absolute terms, the sound wave pressure is 20 Pa) [Lin, 2018]. He considered previously measured threshold values of power densities, starting from which volunteers began to "hear" microwave pulses and took it as 0 dB, and the "traumatic threshold", based on this assumption, should be 10^6 times higher. The average threshold value of microwave radiation for the perception of an acoustic signal by a person according to Lin is about 14 kW/m^2, therefore, the traumatic value will be equal to 14 GW/m^2 [Lin, 2021a; 2021b].

Another criterion, more realistic from our point of view, was proposed in the papers [Dagro et al., 2021; Foster et al., 2021]. They calculated that the traumatic threshold, as in military concussion, would occur at a sound level inside the cranium of about 144 dB (pressure ≈ 300 Pa). According to their calculations, the energy flux in a pulse of about 1 J/m^2 would lead to painful (or traumatic) consequences at microwave radiation frequencies of 1-100 GHz. This flux approximately corresponds to the microwave radiation flux density in the human head area of about 10 MW/m^2 for 0.1 µs. The energy flux of an electromagnetic wave of 1 J/m^2, which is proposed in the paper [Foster et al., 2021], is approximately 140 times lower than the energy flux proposed by James Lin, even if we assume that the microwave pulse duration is 10 ns. Unfortunately, Lin proposed a threshold power density for traumatic impact (14 GW/m^2), but did not indicate for what pulse durations this threshold applies. We discuss this strong difference between pain thresholds below (section 5.4.2), but we will consider both criteria in our assessments, since there are currently no experimental data that could determine a more precise criterion.

/5.4/ Optoacoustic effect as a general physical mechanism of the impact of short electromagnetic pulses on continuous media, including the microwave auditory effect

It is fundamental that the microwave auditory effect occurs without direct impact of electromagnetic waves on the hearing apparatus. Sound in the ears is created by secondary sound waves inside the human cranium. The Frey effect occurs only when irradiated with powerful short microwave pulses with a duration of less than 100 µs. When irradiated with constant microwave radiation, the Frey effect is impossible.

To our knowledge, Havana syndrome researchers have not yet noticed that the Frey effect is a special case of the optoacoustic effect. We do not consider this an unnecessary clarification, since this omission has led to the fact that possible physical causes of some important Havana syndrome incidents have not been considered (at least publicly). Therefore, we will describe the physical mechanism of the Frey effect in more general terms of electromagnetic radiation, meaning electromagnetic radiation in the ultraviolet, visible, infrared and microwave ranges. For all these ranges, the mechanism of the transition of pulsed electromagnetic energy into sound is the same in gas, liquid and solid. It is described by the same mathematical equations for all ranges and all media, and should lead to the same effects.

The optoacoustic (photoacoustic) effect was discovered in 1880 by Alexander Bell, who observed pressure pulsations in a closed gas volume when irradiated with a modulated flow of focused infrared radiation [Bell, 1881]. Based on this effect, Bell created the first prototype of a wireless telephone using electromagnetic radiation – the photophone – and received a patent for it [Bell, 1880]. Unlike Bell's widely used wired telephone, the photophone, and with it the photoacoustic effect, retreated to such a distant periphery for 80 years that none of the first researchers of the microwave auditory effect associated it with the photoacoustic (optoacoustic) effect.

In the early 1960s, powerful pulsed lasers were created. In 1963, Gurgen Askar'yan and his colleagues, using a ruby laser with a pulse duration of 1 µs, due to the rapid heating of liquid in a glass vessel, obtained not only the cavitation effect (the formation of bubbles along the laser beam) and strong sound waves (the optoacoustic effect), but also, for the first time, a shock wave. Not knowing about the experiments of Bell and Frey, they called these phenomena the light-hydraulic effect [Askar'yan et al., 1963]. This term did not enter into practice. Let us estimate the parameters of electromagnetic radiation necessary to obtain the optoacoustic effect.

/5.4.1/ Qualitative mechanism of creating an optoacoustic effect

Qualitatively, the sequence of events during the creation of an optoacoustic effect can be represented as follows. A beam of pulsed electromagnetic radiation with a duration of $10^{-3} - 30\ \mu s$ falls on the irradiated object. The pulse energy is absorbed in a narrow layer, and the substance in the layer heats up very little during this time (from от 10^{-6} до 1-2 ℃). A small but very rapid heating creates a rapid expansion of the substance, and the expanded substance pushes the substance next to itself, and that in turn pushes the new substance in front of itself, and so on. Thus, an acoustic pressure wave is generated. It is in this way that, through rapid heating in a narrow region of the substance, an electromagnetic wave is transformed into an acoustic wave.

To generate sound, and not just heat the substance, the duration of the electromagnetic pulse is critical, because the time of heat supply to a narrow absorbing layer due to electromagnetic energy should be at least 10-100 times shorter than the time of heat loss from the layer due to thermal conductivity and convection [Gusev & Karabutov, 1993]. The ideal situation is when the duration of the electromagnetic pulse is shorter than the time it takes for the sound wave to leave the absorbing layer. In this case, almost all of the absorbed energy of the electromagnetic pulse is converted into acoustic energy. For example, for skin with an absorbing layer of about 2 mm thick and the speed of sound in skin of 1580 m/s, the pulse duration should be shorter than 1.3 µs, which is a typical pulse time for microwave radars and a much longer interval than the pulse duration of serial pulsed lasers (usually 5-100 ns) [Quantel laser, 2024].

The more energy that can be put into the absorbing layer, the greater the pressure of the sound wave. In order for a person to "hear" an optoacoustic sound coming from inside the skull or cranium, this sound must travel to the inner ear. There, the sound activates nerve cells in the cochlea in the same way that ordinary sound coming from the ear (pinna) activates nerve cells in the cochlea. Then the neural signals are transmitted through the central auditory system to the cerebral cortex for human perception. Optoacoustic sound enters not through the "front door" - through the ear, but through the "back door" - from the cranium (bone acoustic conduction) or the brain. The central frequency of the acoustic pressure wave, where the audio signal is strongest, depends on the pulse duration and is approximately $\nu_a[Hz] \approx (0.13 - 0.18) \cdot \frac{1}{\tau_p}$ for microwaves, where τ_p is the pulse duration in seconds [Foster et al., 2021]. For pulses shorter than 4-5 µs, the central frequency of the acoustic wave shifts towards ultrasound and the audible sound can become much weaker, despite the fact that this can cause severe trauma to the auditory system by the mechanical pressure of the acoustic wave, as in a contusion.

/5.4.2/ Quantitative assessment of the creation of the optoacoustic effect

We will give a numerical assessment of the optoacoustic effect using the approach formulated, in particular, in the book "Laser Optoacoustics" [Gusev & Karabutov, 1993]. This approach is widely used not only for microwave and laser imaging in medicine [Xu & Wang, 2006], but also, in particular, for the analysis of Havana syndrome incidents [Foster et al., 2021]. According to [Gusev & Karabutov, 1993; Xu & Wang, 2006; Foster et al., 2021], the acoustic pressure $p_0[Pa]$, which will be created by an electromagnetic beam with a power density $I_0\left[\frac{W}{m^2}\right]$ and a pulse duration $\tau[s]$ will be approximately equal to

$$p_0[Pa] \approx \left(\frac{\beta \cdot c^2}{C_p}\right) \cdot \left(\frac{\vartheta \cdot I_0 \cdot \tau}{L}\right) = \Gamma \cdot \left(\frac{\vartheta \cdot I_0 \cdot \tau}{L}\right), \qquad (2)$$

where c is the speed of sound in the medium (m/s), C_p is the heat capacity of the medium (J/(kg·°C)), β is the coefficient of linear expansion of the medium (m^{-1}), ϑ is the fraction of the power density (energy) of the beam that penetrates the medium, $L[m]$ is the length at which 90% of the energy that penetrated the medium is absorbed $\Gamma = \left(\frac{\beta \cdot c^2}{C_p}\right)$ is a dimensionless quantity that is often called the Grüneisen parameter.

After 25-30 years of intensive research, the physics of the optoacoustic effect (and its special case, the microwave auditory effect) has become clear and transparent. The Grüneisen parameter, the first term of equation (2), is responsible for how effectively the specific electromagnetic energy input into the substance is converted into acoustic pressure, and the second term of equation (2) is simply the specific energy absorbed in the volume of the absorbing layer (J/m^3), which creates rapid heating leading to acoustic pressure.

Let us estimate the parameters of a microwave beam directed to the outer ear area, at which the acoustic pressure with a high probability will reach "traumatic" values for the inner ear ~300 Pa (144 dB) [Foster et al., 2021], or 120 dB (20 Pa) — the pain threshold of the ear [Lin, 2021a, 2021b]. For the skin $\Gamma \approx 0.033$ ($c = 1580\, m/s$; $\beta = 4.14 \cdot 10^{-5}\ °C^{-1}$, $C_p = 3139 J/(kg \cdot °C)$, [Lin, 2021b]), and the fraction of microwave energy transmitted to the scalp will be about ϑ = 0.49, since about half of the microwave energy is reflected from the scalp [Foster et al., 2021]. For a wavelength of λ = 3 cm (a typical wavelength for mass-produced high-power radars), the absorption length in the skin is $L \approx 1.9\ mm$ [Foster et al., 2021]. The "traumatic threshold" in a closed room is reached at a power density in the "target" area of about $I_0 = 36 \cdot 10^6 = 36\ MW/m^2$, and a pulse duration of $\tau = 1 \mu s$:

$$p_0[Pa] = \Gamma \cdot \left(\frac{\vartheta \cdot I_0 \cdot \tau}{L}\right) = 0.033 \cdot \left(\frac{0.49 \cdot 36 \cdot 10^6 \cdot 10^{-6}}{1.9 \cdot 10^{-3}}\right) \approx 306\ Pa. \qquad (3).$$

To achieve a pain threshold of 120 dB (20 Pa) according to Lin with a pulse length of 1 µs, a power density of about $3\ MW/m^2$ is needed (the impact will be strong, but most likely not traumatic). Power densities in the main beam of microwave systems of 3 - 36 MW/m^2 in a closed room at a distance of 30-100 m from the antenna (in the area of the target's head) are the powers of large radars with large antennas and complex rotating structures that can only be placed in stationary rooms or on large multi-ton automobile platforms (section 5.5.1).

This estimate is approximate and to more accurately account for the painful effects of the optoacoustic effect in the human head, it is necessary to conduct experiments on physical models of the head and/or conduct a detailed numerical calculation of the passage and multiple reflection of acoustic waves inside the head, similar to that done in [Dagro et al., 2021], but our estimate gives a realistic idea of the orders of magnitude. We see that the microwave flux density in this calculation is more than two orders of magnitude less than that proposed by Lin [Lin, 2021a; 2021b], but it is still very high and can only be supported by bulky, powerful systems.

In our opinion, the significant difference between the threshold values proposed by [Lin, 2018] and [Dagro et al., 2021; Foster et al., 2021] arises from the nature of the microwave auditory effect, when the effect itself is experimentally recorded by people ("hear – don't hear", "how loud do they hear"), and they "hear" not through the usual auditory mechanism, but through the complex interaction of the sound wave inside various tissues of the head (skin, bone, brain matter) with the cochlea. Apparently, during the Frey effect, the cochlea reacts to sound waves much more weakly than during the usual interaction through the ear and the auditory membrane. Perhaps the Frey effect requires much greater sound pressure for a person to perceive sound than the sound pressure through the ear membrane [JASON, 2021, p. 83]. The optoacoustic approach to Havana syndrome, expressed by formula (2), is independent of human perception and focuses only on acoustic pressure and its possible traumatic impact. Therefore, in what follows, we will use the threshold pressure approach used in the papers [Dagro et al., 2021; Foster et al., 2021].

At the moment, without experimental verification, we can only guess what minimum (threshold) pressure inside the head is traumatic, but with a high probability we can say that a pressure equal to 300 Pa (or more) will cause a person extremely unpleasant sensations, and may even put him out of action for a significant time.

/5.5/ Are there modern microwave systems that can create incidents like the Havana syndrome?

The main argument in favor of the microwave hypothesis was that microwave radiation can penetrate into buildings through walls.

Sound and ultrasound lose almost all their energy when absorbed in the air and, especially, when reflected from any solid surfaces, such as glass, walls, partitions, etc. On this basis, experts rejected the ultrasound version (section 4.3). Laser radiation passes well through transparent media (air, glass, water), but does not pass through any opaque walls, partitions or thick curtains.

In addition, a number of journalists, as well as experts in the Frey effect and even microwave devices, have claimed that there are publicly available, compact microwave systems that can injure people due to the Frey effect, for example [Broad, 2018; Lin, 2021b, p. 13]. These microwave systems, in their opinion, can be relatively unnoticeably placed in small rooms and minibuses (pickup trucks) and carried in a backpack [Broad, 2018]. These claims were supported by the fact that this is a classified area and it cannot be ruled out that there are some new military developments of compact microwave systems that may be unknown to civilian specialists.

Let us consider these arguments in favor of the microwave hypothesis.

/5.5.1/ Microwave system required for indoor microwave irradiation of people

Let us estimate the microwave generator power required to create painful sensations due to the Frey effect based on the formula for power transfer used in radar physics [Johnson, 1993]. The power density is $P_r\left[\frac{W}{m^2}\right] = G\frac{P_0[W]}{4\pi r^2[m^2]}$, where G is the antenna gain. The microwave generator operates at a wavelength of λ with a pulse power of $P_0[W]$ with an antenna area of S (diameter D, antenna area utilization factork_a), distance to the target r and total losses during beam transportation to the target equal to ϑ. For simplicity of presentation and without loss of generality, we will take one of the most common antennas - a parabolic antenna with a cross-sectional area of $S = \frac{\pi D^2}{4}$. The gain of a parabolic antenna is $G = k_a \cdot 5.18\left(\frac{D}{\lambda}\right)^2$ [Benford et al., 2016, pp.32, 443]. The power density of the electromagnetic wave $I_0\left[\frac{W}{m^2}\right]$ in the head area, according to the radar formula, will be approximately equal to

$$I_0\left[\frac{W}{m^2}\right] = 0.412\frac{\vartheta \cdot P_0[W]}{r^2[m^2]} \cdot k_a\left(\frac{D}{\lambda}\right)^2 \qquad (4).$$

The average pulse power of the microwave generator required to create pain or injury for irradiating the target will be equal to, point (1*):

$$P_0 = 2.427 \cdot \frac{I_0 \cdot r^2}{\vartheta} \cdot \frac{1}{k_a} \cdot \left(\frac{\lambda}{D}\right)^2 \qquad (5).$$

An antenna with a diameter of no more than 1.5 m can be realistic from the point of view of stealth and ease of placement in buildings and mobile facilities. Mobile, stealthy work with an antenna with a diameter of 2 m or more seems extremely difficult, point (2*). In order for focusing to be acceptable given the squared ratio of wavelength to antenna diameter $\left(\frac{\lambda}{D}\right)^2$, the wavelength of microwave radiation should be no more than 3 cm.

To achieve the microwave power density near the target's head I_0 = 14 GW/m^2 proposed by Lin [Lin, 2021a; 2021b], which corresponds to the pain threshold, at a target distance of r = 30 meters, a wavelength of λ = 1.5 cm, an antenna diameter of D = 150 cm, an antenna utilization factor of $k_a = 0.7$, and a fraction of the radiation that reached the skin indoors of $\vartheta \approx 0.1$ (we justify this value in detail in Section 6.2), the average pulse power of the generator should be $P_0 \approx 43.7\ GW$:

$$P_0 = 2.427 \cdot \frac{14 \cdot 10^9\left[\frac{W}{m^2}\right] \cdot 30^2[m^2]}{0.1} \cdot \frac{1}{0.7} \cdot \left(\frac{1.5}{150}\right)^2 \approx 43.7 \cdot 10^9\ W \qquad (6).$$

This is currently an unattainable value even for the most modern experimental, not serial generators, especially at such a short wavelength as 1.5 cm [Benford et al., 2016; Benford, 2024]. Moreover, this unrealistic power is greatly underestimated, since we took a small distance to the target equal to 30 m, and with increasing distance, the required generator power grows quadratically. In addition, we took an extremely large antenna in diameter (in terms of stealth parameter) and an extremely small wavelength of the microwave generator, which is currently difficult to achieve for gigawatt-power generators [Benford et al., 2016, pp. 7, 244].

In addition, the cross-sectional area of the waveguide through which all this enormous power will pass to the antenna for a wavelength of 1.5 cm will be about 1.25 cm^2 [Benford et al., 2016, p. 438], which means that the electric fields inside the waveguide according to formula (1) will be equal to an extremely large 3627 kV/cm, which will inevitably lead to a discharge inside the waveguide and blocking the electromagnetic wave even when the waveguide is filled with 40 atm SF_6. SF_6 is a special and expensive gas that is commonly used to prevent breakdown in high-voltage electrical systems, including microwave ones.

The situation will only get worse if we use a wavelength of about 3 cm to use a larger waveguide cross-section, about 2.5 cm^2 [Benford et al., 2016, p. 438]. In this case, according to formula (5), due to the quadratic increase in the ratio $\left(\frac{\lambda}{D}\right)^2$, the required generator power will increase sharply, and it will grow to an even more fantastic 174 GW.

These estimates show that there are no mobile or stationary pulsed microwave generators with capacities greater than 10 GW [Benford et al., 2016; Benford, 2024] that could be used in Havana syndrome-type incidents. Therefore, Lin's pain criterion is unrealistic.

More realistic, as we wrote above (section 5.4.2), are the painful or traumatic power densities proposed by [Dagro et al., 2021; Foster et al., 2021] based on optoacoustic regularities. They are in the range of pulse power densities of 10 MW/m^2 (in the head area) and a pulse duration of 0.1 µs. For a power density of 10 MW/m^2 in the head area, a minimum realistic wavelength of 1.5 cm, an antenna diameter of 1.5 m, a distance to the target of 30 m, a radiation absorption flux by the head of about 10% ($\vartheta = 0.1$) of the initial (section 6.2), according to formula (5), a generator power of about 31 MW is needed (for a distance to the target of 30 m), and 347 MW for 100 m. And in this case, it is extremely difficult to fulfill condition (3*) for the mobile version due to the high power of the system, which makes it very cumbersome. A large modern radar that can solve such a problem will be required.

Examples of such modern radars include the Russian Ranets E system, presented at the 2001 LIMA exhibition in Malaysia. The system has a peak power of 500 MW (pulse duration of 10-20 ns), a microwave wavelength of 3 cm, an antenna size of about 4 m (antenna gain of 45-50 dBi) [Karcz et al., 2023]; as well as the most modern and most compact systems, such as the Tactical High-power Operational Responder (THOR) developed by the US Air Force Research Laboratory [AFRL, 2021; Atherton, 2021]; Specialized Portable Electromagnetic Attack Radiator (SPEAR) by Leonardo DRC [Leonardo DRC, 2022, 2024]; Leonidas HPM System Generation 2, developed by Epirus [Epirus, 2023].

Thus, if microwave systems were used in some Havana syndrome incidents, they were large, powerful, fixed systems. Such systems would have been located in closed, fully controlled premises, which can only be done in cities under the full control of totalitarian or authoritarian states.

/ 6/ Advantages of laser radiation over microwave radiation for creating Havana syndrome-type incidents

/6.1/ Could pulsed laser radiation in principle be responsible for some Havana syndrome-type incidents?

This hypothesis has not been discussed in the publications known to us, although the most advanced calculations of Havana syndrome incidents explicitly used optoacoustic equations [Foster et al., 2021; Dagro et al., 2021; Lin, 2021b].

Let us estimate the parameters of lasers that will allow creating painful or traumatic effects on humans, according to the threshold values proposed for the microwave Frey effect (section 5.4.2).

We are not discussing the optoacoustic effect in general, as it is well studied, but in relation to the Havana syndrome (covert illegal impact), therefore, the laser radiation must be in the invisible to the eye area. It must also pass through window panes without major losses, so that it can effectively irradiate people inside buildings, cars and other vehicles. In addition, the laser radiation must be well absorbed by the skin, but not lead to photochemical reactions in the skin that will be noticed, like tanning or burns. Based on this, ultraviolet lasers and lasers in the visible range are difficult to use covertly in incidents like the Havana syndrome. Therefore, the choice falls on infrared lasers with wavelengths in the range of $\lambda \approx 0.85 - 2\ \mu\mathrm{m}$ (see Figure 2).

In this range, solid-state Nd:YAG lasers with a wavelength of $1.06\ \mu m$ are widely used in industry and medicine, since they are usually the most energy-efficient and reliable. We will choose this type of lasers as an example also because Nd:YAG radiation has an optical penetration depth into the skin, taking into account scattering (absorption depth) of about $L \approx 1.9\ mm$ [Anderson and Parrish, 1981; Bashkatov et al., 2011], which allows us to compare the effect of the Nd:YAG laser with the effect of microwave radiation at a wavelength of 3 cm, where the absorption depth of the electromagnetic wave is approximately the same as that of the laser (see Section 5.4.2).

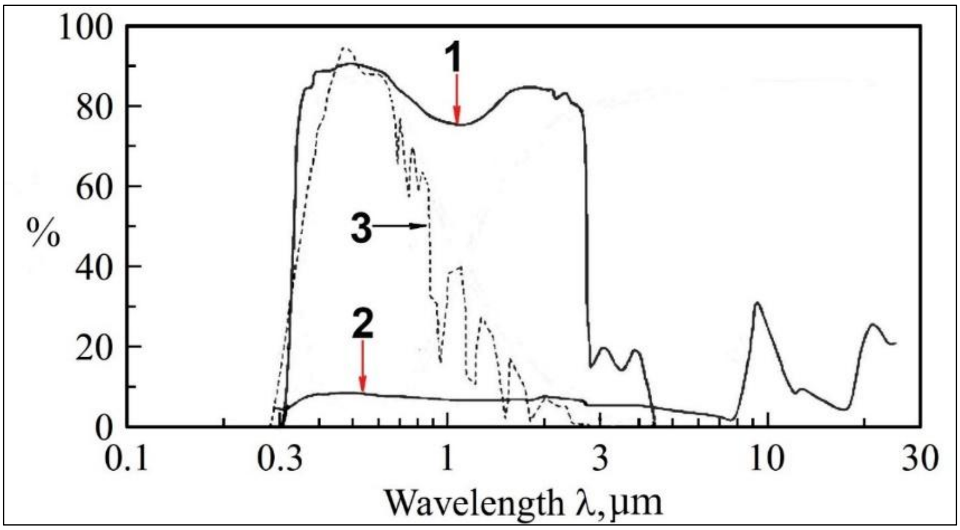

Figure 2. Spectral characteristics of 4 mm thick colorless glass (1, 2) in comparison with the spectrum of solar radiation (3): 1 - transmission spectrum of colorless glass in %, 2 - reflection spectrum of colorless glass in %, 3 - spectrum of solar radiation on the earth's surface. Adapted from [Mayorov, 2018].

Industrial Nd:YAG lasers are produced by many companies in different countries of the world. This is a mass industrial product. As an example, we choose a series of devices produced by Quantel laser, since their technical specifications give us a fairly complete picture of the lasers, and also because the specifications of the ULTRA and CFR models state as one of the main applications: for photoacoustic imaging [Quantel laser. ULTRA, 2024].

All lasers of the considered line, as well as most similar pulse lasers, have very short pulses from the point of view of optoacoustics (5-15 ns). This time interval is approximately 100 times shorter than the time of sound wave escape from the absorption layer of laser radiation by human skin (~1 μs, see section 5.4.1), and even more so, it is much shorter than the times of thermal conductivity and convection. Therefore, we can use formula (2), changing it taking into account the laser parameters, since for lasers in technical specifications the energy in one pulse is usually given.

It was noted above that the main thing in creating an optoacoustic effect is not the total power of body irradiation, but the power divided by a unit of area per unit of time, that is, the energy per unit of area $I_0 \left[\frac{W}{m^2}\right] \cdot \tau[s]$ (J/m^2). Here, lasers have a great advantage over microwave technology, since the wavelength of the lasers we have chosen is 1.06 μm, and the wavelengths of microwave devices that can be used in incidents such as the Havana syndrome are no more than 1.5-3 cm, which is $(1.5-3) \cdot 10^4$ times greater. Any coherent electromagnetic beam with a wavelength λ can be collected at a distance r using lenses and mirrors into a minimal region with a smallest diameter determined by the diffraction limit $d \approx 2.44 \cdot \frac{\lambda}{D} \cdot r$, where D is the size of the smallest mirror or lens in the focusing system [Benford et al., 2016, p.443]. Let us take a microwave wavelength of 3 cm, a parabolic mirror diameter of 150 cm (the maximum possible for security reasons) and compare it with a laser wavelength of 1.06 µm and a glass lens diameter of 2 cm. Since the beam area is proportional to the square of the beam diameter, then, in principle, a laser beam can be focused to a spot at least $1.6 \cdot 10^5$ times smaller than a microwave beam.

Even if the efficiency of energy conversion "from the socket" of microwave devices is approximately 30 times greater than into laser energy, then the energy efficiency of lasers per unit area will still be approximately $5 \cdot 10^3$ times greater than that of microwave systems. This means, in addition to other advantages, which we will discuss in detail below (section 6), that laser systems can be many times more compact and less energy-intensive.

If we want to irradiate “targets” at a distance f with lasers, then the focal lengths of the optical system should also be close to f. The increase in the diameter of the laser beam at a distance f depending on the distance can be estimated using the well-known formula $d \approx f \cdot \Theta$ [Raizer, 2009, p. 367]. Then the area of the laser beam will be $S[m^2] \approx \frac{\pi}{4}(d_0 + f[m] \cdot \Theta)^2$, where Θ is the divergence of the laser beam in radians, d_0 is the diameter of the beam at the laser output. We denote the energy of the laser pulse as $A_0[J]$, ϑ is the energy loss due to reflection and absorption in glass and reflection from the skin, losses on the path, etc. Formula (2) will take the form

$$p_0[Pa] \approx \left(\frac{\beta \cdot c^2}{C_p}\right) \cdot \left(\frac{\vartheta \cdot I_0 \cdot \tau}{L}\right) = \Gamma \cdot \left(\frac{\vartheta \cdot I_0 \cdot \tau}{L}\right) = \Gamma \cdot \left(\frac{\vartheta \cdot A_0}{L \cdot S}\right) \quad (7).$$

We choose a compact air-cooled Viron laser (Nd:YAG laser) with a relatively low pulse energy of 30, 50 mJ, a pulse repetition rate of 20 Hz, a beam diameter d_0 = 3.8 mm and a divergence of less than 1 mrad (< $1.6 \cdot 10^{-4}$) [Quantel laser. Viron, 2024]. Taking into account the small reflection and absorption due to building glass (Figure 2, [Mayorov, 2018]), reflection from the skin is about 7% [Anderson and Parrish, 1981] (93% penetrates the skin), we believe that 65% of the laser energy is absorbed in the skin (0.65 $A_0[J]$). This figure will be substantiated in more detail in Section 6.2. The laser energy absorption layer in the skin will be about 2 mm [Anderson and Parrish, 1981]. Let's take a "reasonable" distance to the target for incidents like the Havana syndrome of 200 meters (not 30 meters, which we took for microwaves, but 6.7 times greater). We substitute these figures into equation (7) and find that the energy in a pulse of 30 mJ is enough to create a deliberately painful (and perhaps traumatic) level of acoustic pressure of ≈320 Pa (∼144 dB), equation (8). To obtain the same level of impact at closer distances, it is necessary to defocus the laser beam, obtaining a larger diameter of the laser spot in the head area.

$$p_0[Pa] \approx \Gamma \cdot \left(\frac{\vartheta \cdot A_0[J]}{L[m] \cdot \frac{\pi}{4}(f[m] \cdot \Theta)^2}\right) = 0.033 \cdot \left(\frac{0.65 \cdot 0.03}{0.002 \cdot \frac{\pi}{4}(3.8 \cdot 10^{-3} + 200 \cdot 0.00016)^2}\right) \approx 320\ Pa \quad (8).$$

Lin's pain threshold (20 Pa, 120 dB) is achieved with a 30 mJ pulse at distances of up to 800 meters.

For another Viron laser model with the same beam divergence parameters, but with a pulse energy of 50 mJ, the “traumatic” level of acoustic pressure of ∼300 Pa (∼144 dB) will be maintained up to 275 m, and the pain threshold up to 1 km. We emphasize that lasers with a pulse energy of 10-50 mJ are “convenient” for this “task”, since they are compact (the weight of the laser with all the accompanying equipment does not exceed 10 kg), do not require large power sources, water cooling and, together with all the additional equipment, can fit in a backpack or a small suitcase. Moreover, a small additional optical unit will allow you to obtain an ultraviolet wavelength of 266 nm (0.26 μm) using the same device, which is also invisible and completely absorbed in glass.

More powerful, but also widely used serial lasers can cause optoacoustic "traumas" at distances of 2.5-3.8 km. For example, the Q-smart-HE series models have a pulse energy of 1-2.3 J (pulse duration of 6-10 ns), divergence of 0.5 mrad, initial beam diameter $d_0 = 10 - 13\ mm$ [Quantel laser. Q-smart HE, 2024]. Let us assume that 65% of the laser energy is absorbed by the scalp (section 6.2). A laser with a pulse energy of 1 J leads to a "traumatic" pressure in the head of $\sim$ 340 Pa at a distance of 2.5 km (the pain threshold of 20 Pa will be at distances of up to 10 km). Let us clarify that lasers with a pulse energy of 1 J cannot be placed in a backpack or suitcase, since the weight of the laser is about 45 kg, the overall dimensions are 50 x 80 x 20 cm, and the electronics and water-cooling unit of this laser weighs 50 kg and has dimensions of 53 x 55 x 80 cm. Such lasers can be placed and camouflaged in an apartment or car [Quantel laser. Q-smart HE, 2024].

Thus, it is technically possible, using widely available small industrial lasers, to create sensations in humans similar to Havana syndrome incidents, with much more compact systems at much greater distances and with much greater efficiency than microwave systems (we discuss other advantages of laser radiation over microwave radiation in Section 6).

/6.2/ Microwave and Laser Radiation Passage Through Walls and Glass

As noted in Section 5.5, the main advantage of microwave radiation over laser radiation is its ability to pass through walls. Laser radiation does not pass through any opaque walls or even thin opaque partitions, while microwave radiation passes through non-metallic walls and partitions, as evidenced by the fact that it is possible to talk on a cell phone inside buildings. Moreover, the penetration of microwave radiation through walls made it the main "suspect" in the "case" of Havana syndrome. Most likely, it is precisely because of this property of microwave radiation that no investigation (including the most detailed investigation by the JASON expert group [JASON, 2021]) has considered lasers as a possible cause of some cases attributed to Havana syndrome.

Consider the propagation of microwave radiation through various obstacles in the frequency range of 3-30 GHz (wavelengths of 1-10 cm). This range is most likely in the case of the use of microwave radiation for incidents like the Havana syndrome. A wider frequency range from 0.8 GHz to 60 GHz has been well studied in connection with the problems of microwave radiation propagation on the “base station-subscriber inside the building” paths (cellular communications) or inside buildings (problems of WiFi coverage of the largest areas). In addition, a whole field of technologies for surveillance through walls using microwaves is being developed. This is necessary, for example, to detect people inside burning or collapsed buildings or to monitor premises where intruders are operating and/or hostages are present [Thiel, 2010].

The interaction of microwave radiation with walls can be divided into three stages.

At the first stage, when microwave radiation falls from the street onto any surface at small angles of 0^0-30^0 for a frequency of 4 GHz (wavelength 7.5 cm) about 50% of the radiation is reflected from a stone wall (Rough Stone Wall), about 40% is reflected from a brick wall, and at least 60%

is reflected from ordinary transparent window glass [Landron et al., 1993] (microwave incidence at large angles sharply increase reflection). For a frequency of 28 GHz (wavelength 1.07 cm), which is more promising for the Frey effect, at an incidence angle of 10^0 the reflection from concrete was 81.5%, from plasterboard - 70%, from clean glass - 74%, and from an outdoor tinted glass wall — 89.6% [Zhao, et al., 2013]. That is, in conservative estimates, one can take the value of microwave radiation reflection from the external walls of buildings to be no less than 50% (0.5), and from window glass no less than 60% (0.6) of the total incident power density.

At the second stage, the microwave radiation that penetrated the wall (glass) will be absorbed by these media. The higher the frequency of the microwave radiation, the stronger its absorption. Even for wood at a frequency of 10 GHz (3 cm), the absorption is 6 dB (4 times) per centimeter of thickness, which, with a wall thickness of only 5 cm, reduces the microwave flux density by 10^3 times. For a frequency of 30 GHz (1 cm), the reduction will reach 10^4 times. For all other opaque walls, the situation for microwave radiation is even worse, since the absorption coefficients and the thickness of solid bricks, cinder blocks, concrete panels are much greater than the thickness of wooden walls and ceilings (see Figure 3) [Shakya et al., 2024]. Thus, even for the thinnest walls and glass, reflection and absorption will reduce microwave radiation indoors compared to open space by at least 20-50 times. But that's not all.

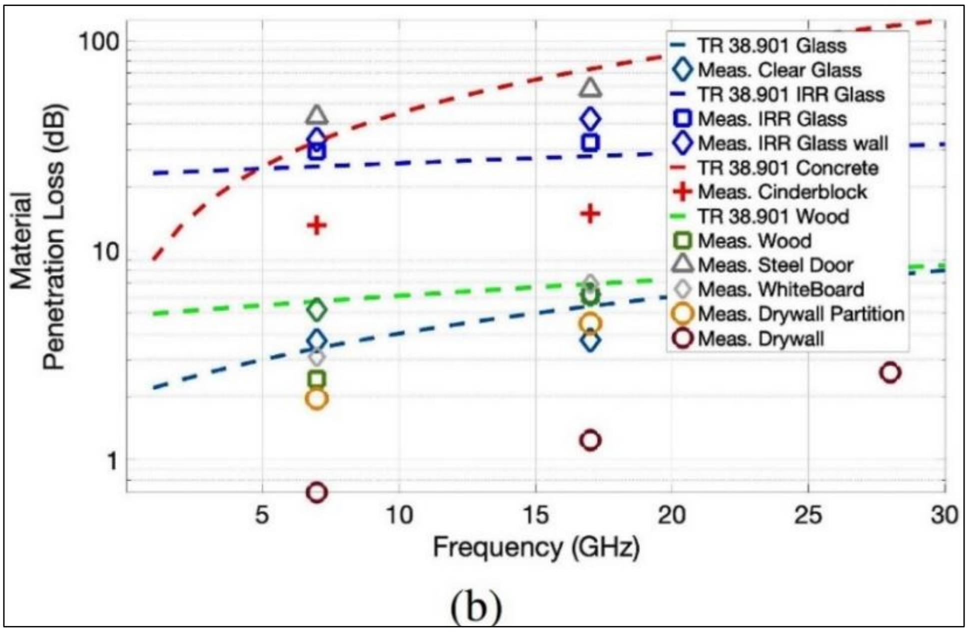

Figure 3. Microwave absorption by different 1 cm thick materials as a function of radiation frequency. Adapted from [Shakya et al., 2024].

In the third stage. The JASON advisory group investigation paid special attention not only to the strong absorption of microwave radiation in the walls, but also to the scattering of radiation after passing through the walls. Based on detailed numerical calculations and measurements of microwave radiation levels [Thiel & Sarabandi, 2009], the JASON experts concluded: "…the signal remains collimated only when there is a direct line of sight to the source (i.e. there are no obstacles in front of the microwave beam - A.K.); otherwise, scattering and interference patterns destroy collimation and spread the beam to scales comparable to the size of the room." [JASON, 2021, pp. 69-71]. This leads to the fact that the area of the microwave beams increases many times, which leads to an additional sharp decrease in the microwave power density that is necessary to implement impacts such as Havana syndrome incidents.

It is important to note that the scattering of microwave radiation is greatly influenced by the periodic structures of the walls, such as brickwork, cinder block masonry or concrete blocks that make up the walls. The walls are usually formed with a thickness of 2-3 bricks or two cinder blocks. There are cavities between the walls, where additional reflection and scattering of radiation occurs. In addition, since the 20th century, almost all bricks and cinder blocks, with the exception of facing ones, are made with cavities inside for heat and sound insulation. These cavities become additional scatterers and create many internal reflections in each brick (cinder block). All this leads to strong additional absorptions and to the splitting of the original beam into several much weaker beams, Figure 4 [Thiel, 2010]. It is these processes that lead to the fact that cell phones sometimes work poorly in buildings.

The processes of reflection, absorption, scattering and passage of microwave radiation through barriers lead not only to a very strong weakening of the radiation power density, but also to the filling of almost the entire building with microwave radiation, which is clearly visible in Figure 5, which shows the distribution of microwave radiation in the space of one floor of the building. In this case, the flux density of the initial microwave radiation falls by 10^2 -10^7 times [Thiel, 2010].

In the entire range of microwave attenuation when penetrating into rooms, there remains a small "window of opportunity", and it is associated with ordinary (not tinted) window glass with an almost perpendicular incidence of the microwave beam on the glass. In this case, the energy loss of the beam when penetrating into the room through the glass can, in the best case, amount to 80% (20% reaches the target) of the power density that reaches the glass. About half of the incoming radiation is reflected from the scalp [Foster et al., 2021]. Thus, we obtain the value of 0.1 (10% absorption by the head) in formulas (5, 6), and this is the largest possible number, since there are usually at least two glasses in a window frame and reflection and absorption occur on each glass.

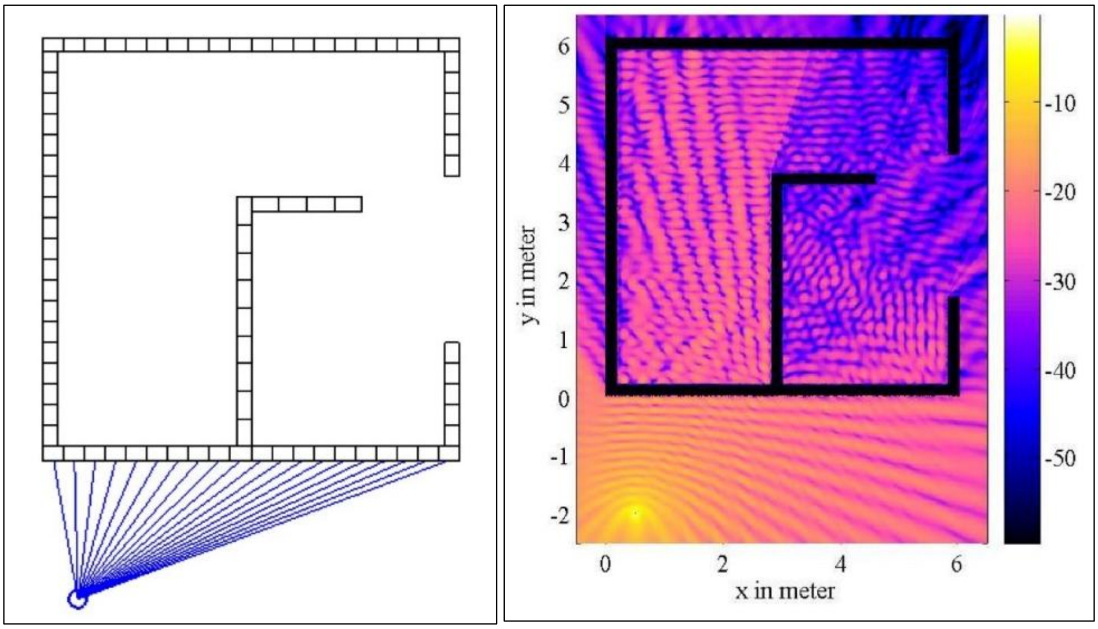

Figure 4. Result of numerical simulation of microwave radiation propagation through brick walls of a complex room (right). The electric field magnitude is color-coded to the right of the color image: the maximum electric field is taken as 0 dB (yellow), and the minimum electric field is taken as -50 dB (dark blue). Adapted from [Thiel, 2010].

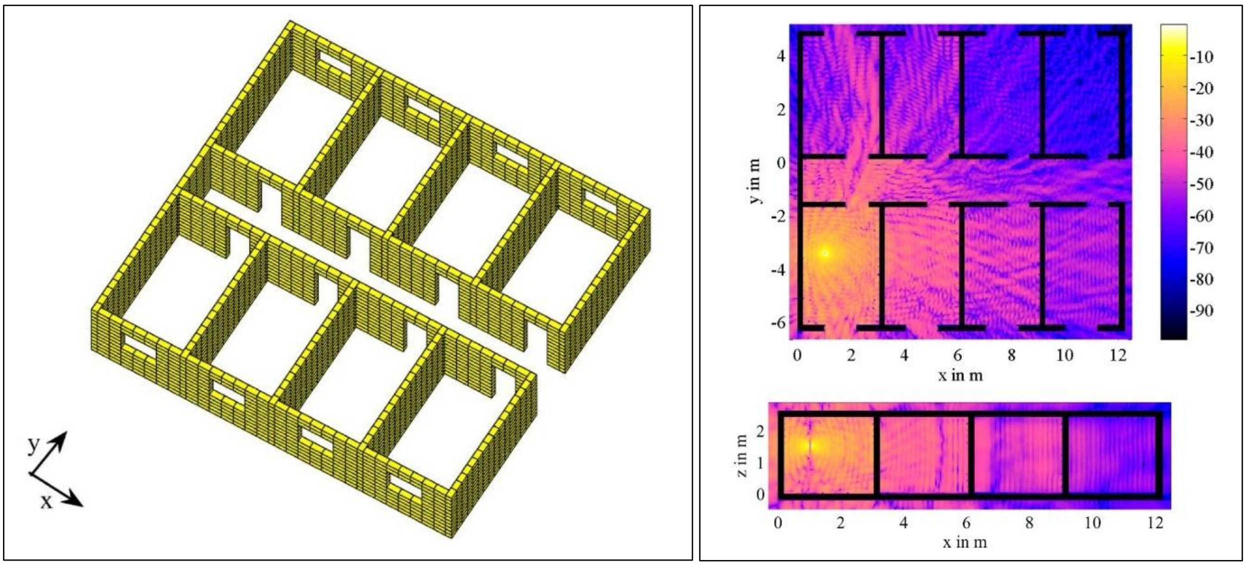

Figure 5. Distribution of the electric field in dB inside the floor of a building with non-uniform periodic walls for vertical polarization. The field value is color-coded to the right of the color image: the maximum electric field is taken as 0 dB (yellow), and the minimum field is taken as minus 90 dB (black). On the left is the floor plan of this office building (floor and ceiling are not shown) [Thiel, 2010].

We come to a paradoxical fact. If we take laser radiation at a wavelength of about 1 μm, then with perpendicular incidence from an ordinary window glass only 8% is reflected (92% passes into the glass), about 75% passes through the glass itself 4-5 mm thick (see Figure 2 [Mayorov, 2018]). Thus, 69% (0.69) of the laser radiation will pass through the window glass, which is at least 3.4 times more efficient than the passage of microwave radiation. If 69% passes through window glass, and only 5-7% of laser radiation is reflected from the skin in the range of 0.25-3 μm (93-95% of radiation incident perpendicular to the head passes into the skin) [Anderson and Parrish, 1981], then we obtain the coefficient of penetration of laser radiation into the skin of the head of about 0.65 in equations (7), (8), section 6.1. Thus, taking into account reflection from the scalp, laser radiation reaching the glass surface of a closed room is at least 6.5 times more effective than microwave radiation reaching the glass.

The figures for microwave power density losses when penetrating buildings lead us to the conclusion that it is impossible to produce painful sensations in a person's head using the Frey effect, due to the powerful pulsed microwave radiation that passes through walls, since it is extremely strongly attenuated, absorbed and scattered by walls and windows. This argument is considered one of the main ones by the JASON advisory group. It makes the microwave hypothesis extremely unlikely [JASON, 2021, p.97-98].

As a result, we come to the conclusion that for Havana syndrome-type incidents, even indoors, lasers are much more “effective” than microwave radiation, since windows are the only sufficiently transparent barrier indoors for Havana syndrome-type impacts, both for microwave and laser radiation.

/6.3/ Microwave and Laser Detection and Stealth

To prevent attacks using any beams of electromagnetic energy, it is first necessary to detect such attacks in real time.

/6.3.1/ Microwave Radiation Detection

Microwave radiation is easily detected by commonly available devices due to strong reflection and scattering both inside and outside buildings (rooms). In addition, any microwave antenna emits microwaves not only in the main beam, but also in the side lobes, which is approximately 5-10% of the radiated power. Therefore, microwave radiation is extremely difficult to "hide". Almost all papers and investigations, starting from the first medical paper [Swanson et al., 2018] and up to the JASON investigation [JASON, 2021], strongly recommended placing microwave radiation sensors of different ranges in and around buildings where there may be targets for "malicious attacks". And these sensors were installed [National Intelligence Council, 2023b]. This is an obvious and important recommendation (and its implementation by at least 2023) should prevent microwave incidents in the future, if any.

Maximum human exposure limits for microwave radiation (less than 10 W/m^2 for public spaces [IEEE, 2019; ICNIRP, 2020]) have led to the development of mass-scale sensitive microwave sensors to monitor public spaces (mainly due to concerns about the negative impact of cellular base stations on people). Also, personal microwave exposure levels for certain occupational categories, such as radar operators or personnel performing commissioning or repair work on cellular base stations, are carefully monitored. Almost always, other cellular operators' equipment located nearby continues to operate during such activities (less than 50 W/m^2 [IEEE, 2019; ICNIRP, 2020]).

Let us take the value of the power density determined by failures in electronics inside buildings (250 x 5) kW/m^2 = 1 MW/m^2 (the increase in the threshold of failures in electronics by 5 times is due to reflections and absorption of microwaves when penetrating into buildings through glass (section 6.2, Appendix 1). At least half of this power supplied to the building will be reflected from the external glass and/or walls of the building and scattering of microwave radiation will begin in the environment surrounding the building with multiple secondary reflections from other buildings. The same will happen inside buildings, Figures 4,5.

Let's take as an example the FR100 outdoor sensor with a frequency measurement range of 0.7 - 18 GHz, a minimum measurable pulse duration of 1 µs (typical for high-power microwave systems), and relatively low sensitivity in the range of 50-1000 V/m (6.6-2700 W/m^2) to measure signal levels in areas covered by radars and cellular base stations, where more sensitive systems may go off-scale or be damaged [MVG-FlashRad, 2021].

If we take a power density of 1 MW/m^2, then in the city between two buildings the microwave radiation will experience about 16 multipath reflections until its level drops below 6.6 W/m^2. We assumed that with each reflection half of the radiation passes inside the walls and glass of the building and leaves the volume between the buildings. This means that for a building about 100 m long, a microwave sensor can be placed anywhere on the facade and it will definitely detect a possible microwave attack. You can also use the 10^3 times more sensitive EME Spy Evolution sensor (0.05 V/m; 6.6x10^{-6} W/m^2) [MVG-EME Spy Evolution, 2020]. Then on city streets the microwave radiation will experience about 36 multipath reflections that can be measured, which means that it will fill an entire city block.

Indoors, the power density of 1 MW/m^2 (the threshold of electronic failure when penetrating through glass) exceeds the reliable sensitivity of sensor measurements (($\sim$10^{-5} W/m^2) by 11 orders of magnitude, i.e. by 110 dB. Judging by the calculations shown in Figure 5, where the microwave signal level drops by 70-80 dB in the far rooms of the floor, it will be possible to detect abnormal microwave exposure at any point in the building, on any floor. Thus, in order to detect in real time an attack by a powerful microwave device that is difficult to quickly dismantle, only two microwave sensors or even one are enough. This fact reduces the chances of “intruders” to practically zero, if the sensors are placed on and/or inside the building. Even microwave devices with much lower power densities, which can presumably be used for espionage rather than to create the Frey effect, will be quickly exposed due to the high sensitivity and selectivity of microwave sensors. As we can see from the report of the US National Intelligence Council, such sensors have already been installed in a large number of government agencies [National Intelligence Council, 2023b].

Microwave personal monitoring devices can also be used [MVG-EME Guard Plus, 2022; MVG-EME Guard XS Radar, 2024]. These sensors record microwave radiation levels, have loud warning sounds when permitted thresholds are exceeded, etc. Such devices weigh between 120-300 grams, are no more than 30-40 cm in size, and can be carried in a briefcase or bag.

/6.3.2/ Detection of laser radiation

Laser radiation is also diagnosed by modern devices, but this is a more complex task compared to microwave radiation. Laser radiation in the range of 1 µm is detected using video cameras with special matrices sensitive in the near infrared range of wavelengths: 0.9-1.7 µm SWIR (Short-Wave InfraRed 0.9 – 1.7µm).

These are fairly common industrial video cameras with indium gallium arsenide (InGaAs) sensors. They are compact and look like regular small cameras, such as [Acuros, 2024]. To cause harm, as discussed above (section 6.1), the laser beam must be powerful enough (0.01-1 J per pulse). In this case, 7-8% of the laser beam energy is reflected and scattered by the glass surface (Figure 2), creating bright spots where the beam contacts the glass. Similar bright spots due to laser reflection will be visible on a human head, since 5-7% of laser radiation is reflected from the skin [Anderson and Parrish, 1981].

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Sunlight greatly complicates the process of detecting laser radiation, since the Sun actively emits light in the SWIR range. For example, the intensity of solar radiation at a wavelength of 1.06 µm is 45% of the maximum intensity of solar radiation in the green region (about 0.5 µm), Figure 2. Sunlight creates a strong general illumination on the SWIR camera lens and reduces the image contrast or makes the laser radiation indistinguishable to the camera. Therefore, in the daytime, laser radiation in this range is not easy to detect with relatively inexpensive SWIR cameras and requires special more complex and expensive methods, the discussion of which is beyond the scope of this article.

It is very difficult to detect laser radiation by its effect on electronic devices. Even very powerful laser radiation will not cause any harm to the electronics surrounding the "target" (unless it is directed directly at it), unlike powerful microwave radiation, which creates strong interference and/or damage to electronics in large spaces. It was the factor of disruption of electronics that was identified as limiting the power of microwave exposure when analyzing the causes of the Havana syndrome [JASON, 2021, pp. 91-94]. Therefore, in order to create the Havana syndrome effect, powerful mass lasers with a pulse energy of up to 50-100 J can be used, which have small beam divergences due to the large length of the resonators. *Thus, the effect of laser radiation is much more covert compared to microwave radiation*.

/6.4/ Availability of Laser Systems Increases the Likelihood of Havana syndrome-Type Incidents in the Present and Future

On March 1, 2023, the US National Intelligence Council (IC) declassified documents titled “An Updated Assessment of Anomalous Health Incidents” [National Intelligence Council, 2023a]. Anomalous Health Incidents (AHI) are events that can be classified as Havana syndrome. This document has an addendum in a separate untitled file [National Intelligence Council, 2023b]. This document, in our opinion, shows that, despite extensive and detailed investigations, there are still significant disagreements among US intelligence agencies about the causes of Havana Syndrome and it is difficult for them to agree on any common language.

On April 1, 2024, a joint investigation by the Russian opposition project The Insider, the American media concern CBS, and the German media concern Der Spiegel was published [Dobrokhotov et al., 2024; Weiss et al., 2024, Croxton, 2024]. They simultaneously published several materials (different from each other), which were based on the assumption that Russian military intelligence officers from Unit 29155 were involved in incidents attributed to the Havana syndrome. The arguments in favor of such involvement were: the presence of identified officers of Unit 29155 in the immediate vicinity of events attributed to the Havana syndrome. The identified servicemen were saboteurs of a wide profile - from explosions to poisonings - and their participation in earlier sabotage activities unrelated to the Havana Syndrome was proven. Perhaps for the first time in the history of the Havana syndrome, data has emerged showing a link between some incidents and the activity of Russian intelligence services.

These publications [Dobrokhotov et al., 2024; Weiss et al., 2024, Croxton, 2024] called microwave radiation the “weapon of attack.” In this they relied on the latest published investigation commissioned by the American intelligence services, in which more than half of the text is shaded in black, there are no references to papers at all (and all evidentiary arguments are based on these papers), there are no formulas or scientific graphs, but there are large illustrative pictures [IC Experts Panel on AHIs, 2022]. However, we note that these events occurred after the American government agencies equipped American institutions and, possibly, individual employees abroad, with highly sensitive means of monitoring microwave radiation levels [National Intelligence Council, 2023b]. This fact reduces the likelihood of using microwave technology (see Sections 6.3.1).

Could trained saboteurs (no matter from which country) use high-power microwave radiation in these new incidents? In our view, no (sections 5, 6). Could they use lasers? In our view, yes. With a much higher probability and lower costs and risks (sections 6, 7).

/7/ Conclusions

<1> Most incidents attributed to the Havana syndrome are well explained by the psychogenic hypothesis.

<2> It is highly likely that microwave exposure was not the cause of incidents attributed to the Havana syndrome phenomenon.

<3> When studying incidents of the Havana syndrome type, it is necessary to take into account the scenario of using laser radiation, as the simplest mechanism for creating an optoacoustic effect in the human head:

<3.1> The main advantage of lasers over microwave systems is that it is technically possible to create pain sensations in humans similar to Havana syndrome using widely available, inexpensive, small, easy-to-use industrial lasers, and at much greater distances and with much greater efficiency, including irradiation of targets in closed spaces (Sections 6.1 and 6.2).

<3.2> Using fiber cables, laser radiation can be output to any convenient location at a large distance from the laser. Laser wavelengths of about 1 μm are also convenient in that they allow the use of inexpensive and common fiber cables and mass-produced glass lenses for focusing the beams. Microwave systems are rigidly tied to antennas or arrays of large-sized active phased array semiconductor elements for good focusing.

<3.3> The laser together with the control and cooling system (for powerful lasers) can be placed in the trunk or body of a car, and the laser beam, thanks to fiber optics, can be emitted from the area of headlights, antennas, parking lights, etc. When using lightweight models of air-cooled lasers with a pulse energy of 10-50 mJ, which are placed, for example, in a backpack, the laser radiation can be output, thanks to waveguides, depending on the "task" through many points on a person's clothing. Microwave systems with a power of even several megawatts (not hundreds) cannot be placed in a backpack, suitcase and are very difficult in a pickup truck or minibus.

<3.4> Laser radiation can be directed to many targets in less than a second thanks to acousto-optic deflectors [Gottlieb et al., 1983].

<3.5> Even powerful laser radiation will not cause damage to the electronics surrounding the "target" (unless it is directed directly at it), unlike powerful microwave radiation, which creates strong interference and/or damage to electronics in large spaces. Laser radiation scattered on the "target" will remain inside the room where the "target" is located, unlike microwaves, which can spread throughout all the rooms of the floor and even the building. This greatly increases the secrecy of exposure using a laser compared to microwave radiation (section 6.3).

<3.6> Lasers are much more effective than microwave radiation in creating pain sensations using the optoacoustic effect in the cranium of a person located in the room (since windows are the only sufficiently transparent and low-scattering barrier for exposure to both microwave and laser radiation (section 6.2).

<4> The availability of technologies for creating a laser optoacoustic effect in the human cranium expands the circle of both state and non-state actors who could and may be involved in future incidents like the Havana syndrome.

<5> It is necessary to improve collective and personal diagnostics of possible impacts on personnel (using sensors) in all relevant ranges of electromagnetic waves (ultraviolet, visible, infrared and microwave), and possibly also in the acoustic range.

Acknowledgments

The work on this article was not supported by any state or private funds or individuals. It was made solely and only on the initiative of the author and at his expense. The author is grateful to Olga Orlova and M.B. for their great contribution to editing the paper, and to Vladimir Gubailovsky, Eugene Koonin, Alexander Sergeev, Maxim Solyus, Andrey Tsaturyan for valuable comments and suggestions.

APPENDIX 1

Maximum Possible Power Densities and Electric Field Strengths During Possible Havana Syndrome Incidents

The upper limit of microwave power density is not determined by the electric field of microwave breakdown of air 30-32 kV/cm (3-3.2 MV/m; 2.4 GW/m^2), as stated, for example, in [Lin, 2021b], but is determined by electric fields in which discharges are initiated by sharp metal (conductive) objects and/or initiated at the points of contact between metal and dielectric (this is how almost all electronic microcircuits are designed). These thresholds are in the range of 0.6-1 kV/cm (60-100 kV/m) [Brodskii et al., 1983].

Our estimates show that microwave power densities in the head region that cause pain (or injury) can be in the range of 3 – 36 MW/m^2 (33.6-116 kV/m) (Section 5.4.2). These electric fields can not only damage electronics, but also create small discharges on metal parts of glasses, earrings, necklaces, dental implants (when talking), etc., which the exposed people could not help but notice (or feel). But even these high-power densities were calculated on the condition of 80% losses when passing through one glass pane in a building (Section 6.2). Therefore, a power density 5 times higher (15-180 MW/m^2) must be supplied to the glass, which corresponds to even higher electric fields (75-260 kV/m).

These electric fields will almost always create discharges on sharp metal edges of glass fastenings in window frames and on their metal handles, on tree branches and leaves, on wires that hang in the plane of windows, etc. This effect is well known, many people have seen it (and heard crackling discharges) when accidentally placing metal objects in a microwave oven. But inside household microwave ovens, the electric fields (∼20-40 kV/m) are much smaller than the 33.6-116 kV/m discussed above, not to mention 75-260 kV/m. Therefore, the real upper threshold of microwave radiation power densities that could be used in incidents like the Havana syndrome does not exceed 27 MW/m^2, which is at least 88 times less than the breakdown threshold of clean air.

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