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Using Signals of Opportunity to Experience and Understand HF Ionospheric Radio Propagation

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Abstract

This paper will investigate and observe the use of signals of opportunity to enable undergraduate engineering students to experience and thereby better understand how the *E* and *F* layers of the ionosphere can enable intercontinental reception of high frequency (HF) radio signals and how the *D*-layer affects radio propagation. Signals of opportunity could be NIST's WWV at 2.5, 5, 10 and 15 MHz; Canada's CHU at 3.33, 7.85 and 14.67 MHz as well as the BBC and other international short wave broadcast stations. Unless deflected, wireless distances are line of sight on the order of 50 km. Ground wave, tropospheric, and other effects make possible communication distances beyond line of sight. However, HF signals that deflect off the ionosphere can enable reliable communication distances in excess of 4000 km, and with multiple hops can span the entire globe. In addition to answering the question of the how and why of ionospheric or sky wave propagation, we will also discuss and show how students can directly experience the various limitations such as what occurs during day light hours when signals at the lower portions of the HF band are absorbed by the *D* layer and thus do not propagate much beyond line of sight, and how solar events such as sunspot cycles and solar eclipses affect ionospheric or sky wave communication. Building on this knowledge, students will better understand radio propagation and explain why everyday AM broadcast, and FM radio signals coverage is local only, but each exhibit different properties. Furthermore, students will better appreciate the necessity of frequency diversity to achieve more reliable wireless communication.

Introduction

Radio waves, like other light waves, unless deflected, normally travel in a straight line. The means of deflection include diffraction, refraction, reflection and scattering. These enable radio waves to travel beyond the curve of the earth and under certain conditions, achieve intercontinental wireless communication. When radio was first developed, intercontinental wireless communication was done at the medium, low and very low frequency bands (MF, LF and VLF)[1] where wave propagation is mostly the result of diffraction around the earth's surface and/or the surface wave being guided by a conductive earth in the same way of what would occur on a transmission line. This is referred to as *ground wave* or is sometimes called the "Norton surface wave." [1,2] and is illustrated in Figure 1. Because of the earth's limited conductivity, it takes a relatively large amount of power to overcome ground losses (in addition to spherical dispersion losses) and these ground losses increase as the frequency is increased. Hence, this is why practical ground wave communication is limited to the MF and below bands (i.e. below 3 MHz). Another means of radio propagation is tropospheric bending where waves travel beyond line of sight via refraction in the earth troposphere region. Tropospheric bending is an interesting subject for study, but will not be considered here. See references [2] and [3] for more information on tropospheric propagation. Waves can also be deflected by reflection, or scattering from terrestrial and even extraterrestrial objects (i.e. buildings, hills, meteor trails, the moon, northern and southern lights, etc.), but these mechanisms will also not be considered.

[1] The VLF band runs from 3 to 30 kHz, the LF band runs from 30 to 300 kHz, the MF band runs from 300 kHz to 3 MHz, the HF band runs from 3 to 30 MHz, the VHF band runs from 30 to 300 MHz and UHF band runs from 300 to 3000 MHz.

Again note from Figure 1 that given sufficient power to overcome ground and other losses, signals could propagate via ground wave from one point to almost any other point on the earth. That all stations in the propagation path are reachable, with no destination skipped over. This universal coverage property is especially useful in naval communication and terrestrial navigation (e.g. LORAN) where the source and destination locations may be constantly changing.

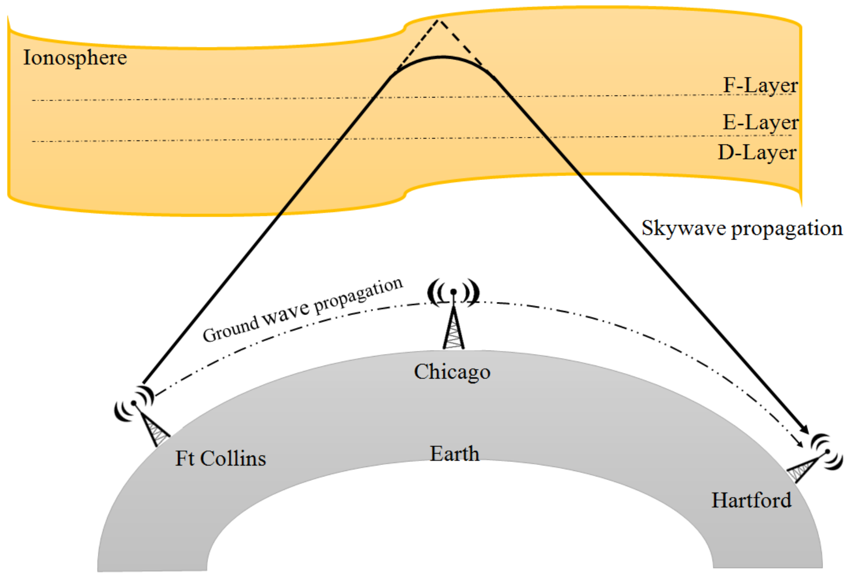

Figure 1. Groundwave and sky wave propagation

Sky wave or ionospheric propagation will be the focus of this paper, and it occurs when a radio signal is "reflected" off the earth's ionosphere as is illustrated in Figure 1. We use the term "reflected" somewhat loosely, when in fact, in most cases, the signal is really refracted as shown in the upper portion of the Figure 1. Depending on the angle of departure, etc. signals can travel as far as 4000 km on a single hop, and even further on multiple hops. Sky wave is the sole means for long distance propagation in the HF or shortwave bands (3-30 MHz). It can also occur in the MF bands, and depending on space weather (e.g. sunspot activity), will also occur on the lower portions of the VHF (very high frequency) band. One interesting point is in the MF band where signals can be effectively propagated using both ground wave and sky wave such that for a given transmission, both may occur, and signals could experience multipath interference.

In the early years of radio, scientists thought that the ionospheric propagation for HF communication was unreliable for long distance communication. It was highly dependent on the time of day and year, the frequency, sunspot activity and other space weather, and because the signal reflected off the ionosphere, coverage would be spotty. For example, observing Figure 1, a signal could travel from Ft Collins, to Hartford, but Chicago would be missed. Because of these seemingly theoretical limitations, until the early 1920s, scientists and engineers all but wrote off the high frequency (HF) bands for serious long distance communication.

However, ham radio operators were not aware of these limitations and simply went ahead to experiment with and exploit the HF bands for personal communication. They soon discovered that by being flexible with the time of day, and experimenting with different frequencies, and antenna types, a relatively reliable system of long distance communication in the HF bands at significantly lower power levels as compared to the MF and LF bands could be accomplished. For example, for most of the day and much of the night, stations could achieve transcontinental and intercontinental communication at 14 MHz. or during the night at 7 MHz. It could be said that these hams, using their experimental methods were the original “crowd sourcing” that increased our understanding of ionospheric communication.[2] The empirical results caused further investigation of the ionosphere as a viable means for radio propagation.

In any case, the tremendous utilization of the HF bands by the experimentalists and their success in achieving reliable communication as well as improved receiver and transmitter technology encouraged commercial and government entities to start using the HF bands for shortwave broadcasting and other worldwide wireless communication. The military also seized on this opportunity for long distance communication but also incorporated relatively crude frequency diversity (i.e. if one channel did not work, try another) and/or antenna diversity to achieve even greater reliability. Before the development of satellite relay, HF was the primary means for long distance wireless communication.[3] Starting in the 1960s, however, satellite relay at and above the VHF bands started to supplant HF as a means to achieve long distance wireless communication.

Today, with the advances in digital communication technologies, there is renewed interest in using HF as a means for long distance wireless communication both as a backup to satellites, and for polar communication. Thus there is an interest for students and engineers to better understand ionospheric propagation. A necessary component for increased understanding and insight is by means of empirical testing or in today’s education parlance, in order for one to really understand sky wave, one has to experience it.

In subsequent sections of this paper, we will first review the basics of sky wave radio propagation including basic optic theory and how ionization in the *E* and *F* layers will deflect radio signals. We then describe some experiments using simple low cost equipment so that students can experience and thereby better understand sky wave. In addition to answering the question of the how and why of sky wave, we will also describe various limitations such as what occurs during day light when signals at the lower portions of the HF band are absorbed in the ionosphere’s *D* layer and thus do not propagate much beyond line of sight, and that seasons and solar events such as sunspot cycles and solar eclipses affect sky wave communication. With this knowledge, students will better understand radio propagation and explain why everyday AM broadcast, shortwave, and broadcast FM radio signals exhibit different distances and behavior (e.g. noise). Furthermore, students will better appreciate the necessity of frequency diversity to achieve reliable sky wave communication.

Theory

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[2] Ed Tilton, of ARRL who in the 1960s attended a dedication ceremony for WWV’s FT Collins transmitter, noted that in a speech given by Dave Packard or William Hewlett made the bold statement that every worthwhile discovery in radio propagation was made by Ham radio operators.

[3] The Navy continues to use the LF and lower bands for ship communication.

Basic optics - When a radio or light wave goes from one media to another, depending on the new media's properties and the light's wavelength, the wave can either be reflected, refracted, or both. This is shown in below in the ionized media of Figure 2. Note the incident and reflected waves are traveling through a media of refractive index, n_1 and the transmitted wave is refracted in a second media with index n_2. The angle of incidence is equal to the angle of reflection so that $\theta_1 = \theta_3$ and Snells law of refraction states that $\frac{\sin\theta_2}{\sin\theta_1} = \frac{n_1}{n_2} = \frac{v_2}{v_1}$ where v_1 and v_2 are the respective phase velocities through media 1 and 2. A more extreme case of refraction is shown in the upper portion of Figure 1 when a wave enters a non-uniform media, the angle of refraction will change causing the signal to be travel horizontally and then may even bend back so that it returns and thus appears to be "reflected." Chapter 17 of Jordan et al. [2] describes this in more detail. This property is what enables HF radio signals to bend back to earth and thus enable long distance radio propagation.

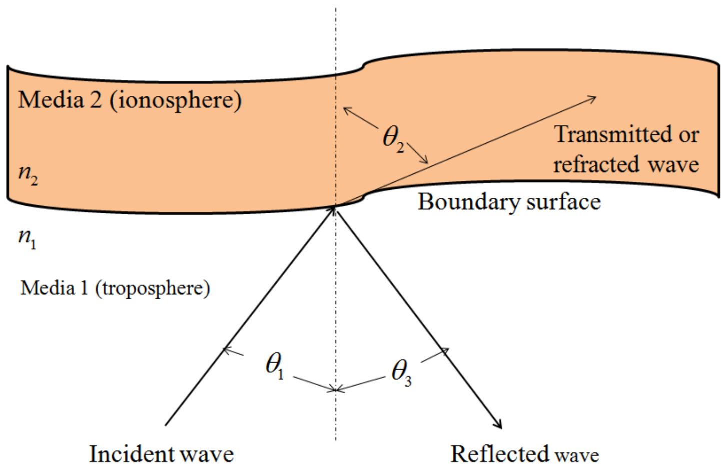

Figure 2. Reflection and refraction through ionized media.

If the media #2 were a perfect dielectric, there would be no loss of power in the transmitted wave. On the other hand, with if the media is ionized, then depending on the gas type, at some frequencies, the media may be conductive and thus signals would be absorbed. It should also be pointed out that the dielectric constant $k = \varepsilon_r$ is related to the index of refraction by $n = \sqrt{\varepsilon_r}$. In the case of the ionosphere, these parameters are not necessarily uniform across the ionosphere or even across a particular ionospheric layer. Neither are they time-invariant. Specifically, their properties are subject to changes in solar weather and the ionosphere's position relative to the sun (i.e. time of day or season). See [2] for more information on these parameters and the theory of reflection and refraction of electromagnetic waves.

Ionization – Ionization is a process whereby an atom or molecule becomes charged either by losing or gaining electrons. In this case we will assume the ionized molecules are gaseous. An ionized gas is also called a *plasma* [4]. This process is initiated when there is a strong external electric field, or external radiation. External radiation can be from ultra-violet rays, gamma rays, x-rays, etc. Visible examples of ionization would be an electrical arc across an air gap as occurs in a spark plug or power line corona. In the case of radio propagation, the source that excites the gas atoms in the ionosphere would be from the sun's radiation. An ionized gas has properties of conductivity, σ, permittivity, $\varepsilon = \varepsilon_r \varepsilon_0$, and reflectivity, r. Their values are a function of the type of gas, its density, and the amount of energy used in ionizing. Like other media, how it affects the incident wave is also a function of the incoming wave's frequency. Thus when an incident wave, reaches the plasma, it may be refracted, reflected or absorbed. LF and below signals are reflected and/or absorbed, HF signals are refracted and/or absorbed and VHF signals are not much affected and thus pass through the ionosphere with little loss. This is one of several reasons why satellites use the VHF and above bands. See Jordan et al. [2] for more information on these parameters.

Another reason the ionosphere does not have uniform properties is because the ionized gas is also magnetized by the earth's natural magnetic field. This magnetization creates two different refractive indices. It is beyond the scope of this paper to describe all the implications of this property, but the reader is encouraged to see Nichhols [4] for more information.

HF ionospheric propagation – The troposphere extends to about 10 km[4] above the earth's surface and in this region, much of the solar radiation has already been weakened by absorption and thus there is little ionization. Even if there is enough solar radiation for ionization, the molecular density is sufficiently high to cause quick recombination of the ions and electrons. At the furthest distance of the earth's atmosphere, beyond 1000 km, with high radiation levels, the gas density is extremely low, and thus there are few molecules to be ionized. Between these extremes is the ionosphere. Here, there is sufficient solar radiation and molecular density to create a significant amount of ionization to refract, reflect, and/or absorb HF radio signals. The ionosphere contains different types of gasses which when ionized will have differing properties. Hence, the three distinct regions that form the *D*, *E* and *F* layers.

The *D* layer starts at about 60 km and has a relatively high conductivity and therefore absorbs signals below 5 to 8 MHz. It has little persistence and thus is only present when directly illuminated by the sun (i.e. during the day). The *E* layer starts from 100 to 115 km and the *F* layer starts at 160 to 200 km and extends to about 400 to 1000 km. The *E* and *F* layers refract MF, HF and sometimes VHF signals and are thus responsible for long distance MF, HF and VHF propagation. The *E* and *F* layers are more persistent than the *D* layer and are present long after the sun has set. Because *D*-layer absorption occurs only during daylight hours explains why only local AM broadcast signals (550 kHz to 1700 kHz) can be heard during the day, whereas at night, signals from AM broadcast stations can propagate thousands of km across the country. On the other hand, signals above 8 to 10 MHz are not affected by the *D* layer and hence these can be heard during the day and most of the night. There is an upper limit on the frequency of the signal than can be deflected by the ionosphere and is called the *maximum useable frequency* (MUF). In general, it is approximately 15 MHz but will greatly vary according to the time of day, time of year, prevailing solar weather and the signal's angle of incidence [2]. For example, in the 11 years sunspot cycle, during sunspot maximum, the MUF will often, but intermittently exceed 30 MHz. See references [2] and [3] for more information on ionospheric propagation.

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[4] The stratosphere runs from 10 to 60 km above the earth.

Above the MUF, signals are generally not affected by the ionosphere and unless there are other deflection mechanisms, signals will not travel much beyond line of sight. [5]

Experimental

Experimental testing and observations: Our experimental apparatus consisted of a Kenwood TS590 short wave receiver and an end-fed, 100 foot wire antenna strung around the woods of Connecticut. The receiver is shown in Figure 3. In order to improve the ability to receive weak signals, the product detector was used. No attempt was made for impedance matching and as a result the measured SWR was relatively high. The 100 meter long wire antenna was "L" shaped, and was oriented both north-south and east-west directions.

Figure 3. Receiver used for reception of HF signals.

Signals of opportunity we initially chose were Canada's CHU time/frequency beacons at 3.33, 7.85, and 14.67 MHz and NIST's WWV time/frequency beacons at 2.5, 5, 10, and 15. Both of these are large carrier AM sources and transmit their signals 24/7. Reference [3] lists other possible stations that transmit time and frequency signals. These include locations in Argentina, Russia, and China. CHUs transmitter is located in Ottawa with a distance to CT of 470 km. WWV's transmitter is in Ft Collins, CO and its distance to CT is 2700 km. One could also choose other international shortwave stations such as the BBC or Voice of America. WWV also transmits a 20 MHz signal, but it was never received and thus the MUF for most if not all of October 2018 was below 20 MHz. This could change with the seasons and/or space weather conditions. We also listened and observed that only at night, long distance AM broadcast signals could be heard.

When starting the initial testing, it was found that regardless of the time of day, CHU's 3.33 MHz beacon was always strongly received. Given the relatively close distance from Ottawa to Connecticut, and its 3.33 MHz signal which if propagated via the ionosphere, would be subject to *D*- layer absorption, sky wave propagation was ruled out, and thus CHU-3.33 propagated only via ground-wave. The two other CHU signals could be heard at night, but were relatively weak as

[5] Tropospheric bending can occur in various degrees in the VHF and UHF bands and thereby extends the reception distance. The northern and southern lights when they occur, will also deflect VHF signals.

compared to the WWV signals and so it was decided to just monitor the WWV signals. Other receiver locations and/or antenna designs may give different results.

To get an initial sense of the WWV's signals, we monitored them from July to October. The 2700 km distance from CO to CT and how much the strength of the received signals varied according the time of day, confirmed a sky wave transmission path.

On October 18, 2018, over a 24 hour time interval, at the top of each hour, the 2.5, 5, 10 and 15 MHz WWV signal strengths were recorded on a spreadsheet and graphed as shown in Figure 4. Signals strengths were assigned on a scale of 0 to 4 with a 4 being the strongest and a 1 when only a carrier tone was heard.

The results confirm what is generally expected about ionospheric propagation. In looking at Figure 4, observe the following. (a) the 2.5 and 5 MHz signals can only be heard at night indicating that when the sun is out, the *D*-layer is present and absorbs signals on the lower part of the HF bands and thus prevents them from reaching the *E* or *F*-layer for long distance transmission. Note that the sunset/sunrise in Colorado lags Connecticut by two hours as well as other considerations means that receiving these will not necessarily coincide with the exact local sunrise/sunset times. (b) The 5 MHz signal is less subject to the *D*-layer than the 2.5 MHz signal and is thus heard for a longer time during the daylight hours. Therefore, we observe *D*-layer absorption is frequency dependent such that the higher the frequency, the less the absorption. (c) The 10 and 15 MHz signals are heard during much of the 24 hour interval which again confirms that signals above 5 MHz, are free to reach and propagate via the *E* or *F*-layer. (d) The ability of the *E* or *F*-layer to propagate 10 and 15 MHz signals does not start until the sun has risen and thereby illuminating the ionosphere for all three time zones (Eastern, Central and Mountain) and ends at some time after the sun has set in the three time zones. Ionization does not immediately end when the sun sets, but the ionization level for these frequencies does decrease over time. Given that the 10 MHz signal continues to propagate long after the sun sets suggests that the 10 MHz signal requires less ionospheric ionization as compared to the 15 MHz signal.

D-layer absorption of the signals in the lower portions of the HF band and below also explains and confirms that far-away AM broadcast stations can and will only be heard at night. Thus to prevent interference with other far-away broadcasters, the FCC requires some local stations to go off the air or lower their power at sunset. This is easily observed by listening to AM broadcast radio at noon and noting the stations heard, and then repeating this at midnight.

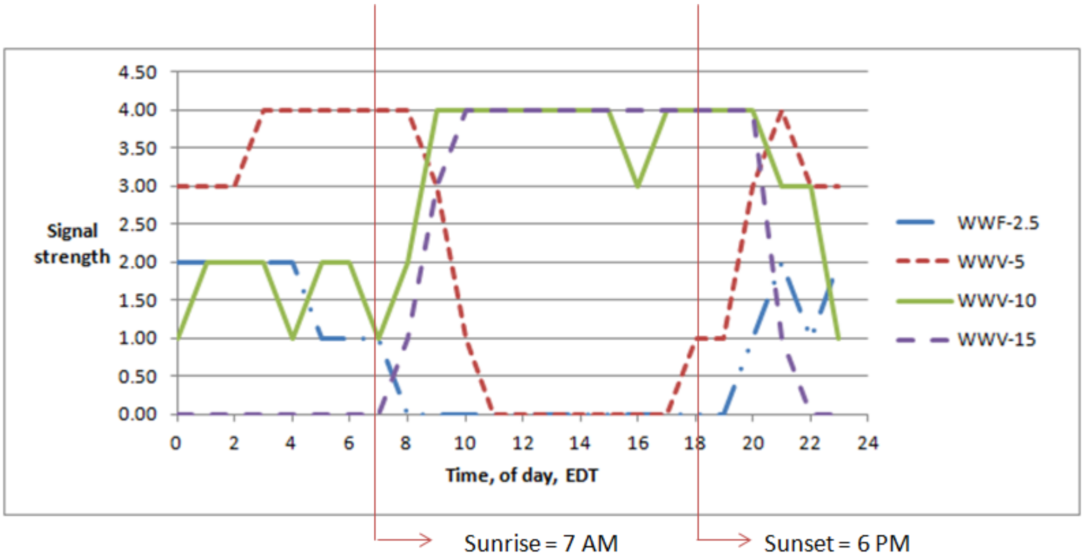

Figure 4. Signal strength versus time of day for the WWV signals at 2.5, 5, 10 and 15 MHz. Note that 0 = midnight, 2 = 2 AM etc. Measurements taken at Old Lyme, CT, October 2018.

Other observations: In observing the signal strength plots of Figure 4, and then by extracting the maximum values for each frequency, the graph of Figure 4 is obtained. As Figure 5 indicates, throughout the 24 hour interval the signal is strong or very strong. Thus one of the WWV signals can always be received regardless of time of day.

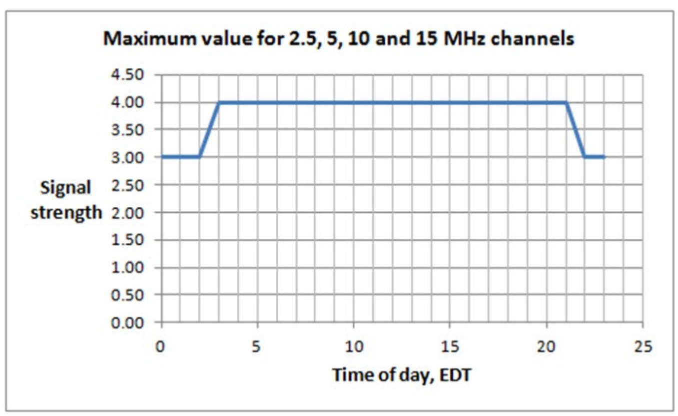

Figure 5. Maximum signal strengths of for 2.5, 5, 10 and 15 MHz of above Figure 3 that show the benefits of frequency diversity.

Conclusions

By using a basic short wave receiver, and an easily constructed wire antenna, students can observe and experience transcontinental sky wave propagation. They observe that far away signals on the lower portion of the HF band are only heard between sunset and sunrise and that at the frequencies above 5 MHz, signals can be heard most of the day. By seeing how signal strength is both a function of frequency and time of day, students can better appreciate the necessity of frequency diversity to ensure a reliable communication system. There are other benefits to this listening exercise. The first is that they can readily observe the superiority of the product detector over the envelope detector for weak signal reception. Secondly, when listening, students will notice "static crashes"- burst noise, and thus with digital communication, understand the necessity of employing bit interleaving when using forward error correction. In other words, unlike Gaussian white noise which occurs in the receiver's electronics, burst noise from the HF channels does not merely corrupt random bits, but can wipe out an entire frame. Thirdly, unlike the VHF and above bands, students will readily observe that the main source of noise is in the HF channel and not the receiver electronics. This is observed when disconnecting the antenna and how much the background noise in an HF receiver goes quiet whereas on the VHF bands, the background noise is constant with or without an antenna. Finally, students can readily observe what frequencies are appropriate for re-use. In other words, they see which broadcast types can simultaneously transmit on the same frequency and be received by their intended audience without interference if they are separated by some minimum distance. Examples of frequency re-use are with FM and TV broadcasters which use the VHF bands, and during the day with AM broadcasters. On the other hand, HF and below signals because of their long propagation distances generally are not re-used or at least if they are, it is understood that there will be interference.

Our experiments have been with signals traveling east-west. It would be useful to also consider characterizing HF and VHF signals from the southern hemisphere to determine if there are any equatorial effects. Another interesting exercise would be to make HF measurements during a solar eclipse.

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