The Rebirth of HF

White Paper

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1 Introduction

HF stands for “high frequency” and is usually used to refer to signals with frequencies in the range of 3 MHz to 30 MHz, although in many cases the practical definition of HF has be extended down to frequencies as low as 1.5 MHz. HF is also sometimes referred to, somewhat loosely, as "shortwave," especially in the context of broadcasting. These HF frequencies correspond to wavelengths in the range of approximately 10 to 100 meters. Given that modern homes contain Wi-Fi access points operating in the gigahertz range and that some 5G deployments are taking place in so-called millimeter-wave bands, the names “high” frequency and "shortwave" may seem a bit misplaced, but it is worth nothing that the first experiments in long-distance radio communication by Marconi around the year 1900 used even lower frequency signals.

One of the best known applications of HF is worldwide or global communications. Both government and commercial broadcasters can reach listeners worldwide using HF frequencies. This global reach is also extremely useful in many government and military applications, and HF is used extensively by amateur radio operators around the world. This paper will begin with an exploration of the unique properties of HF that enable global communications.

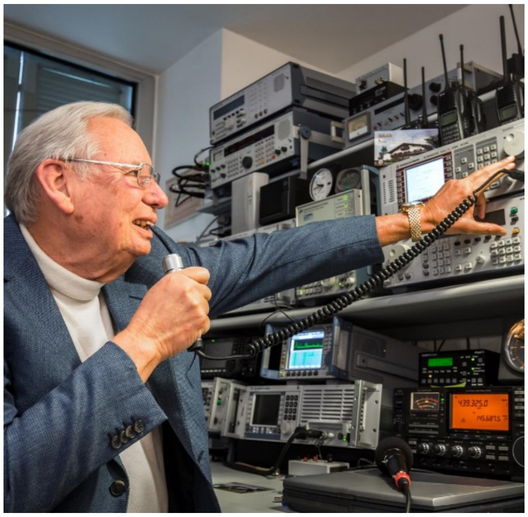


Figure 1 - Amateur radio operator Dr. Ulrich L. Rohde, DJ2LR / N1UL, operating on HF

2 HF Propagation

2.1 HF propagation modes

The same propagation phenomena that allow worldwide communications on HF are however also highly variable and somewhat unpredictable compared to communications at other frequencies, such as VHF and higher. As a result, the greatest challenge in using HF for communication usually consists of finding the optimum frequency for communicating with the intended destination under the current propagation conditions.

Although there are numerous more "exotic" modes of HF propagation, there are three main ways in which HF signals propagate: line of sight, groundwave, and skywave.

2.1.1 Line of sight

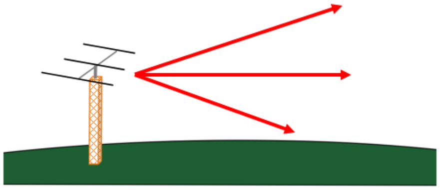


Figure 2 - Line of sight or direct wave

Line of sight, also referred to as "direct wave" is fairly self-explanatory: signals propagate in a straight, unobstructed path between the transmitter and the receiver. Line of sight is the only HF propagation mode which remains is fairly constant – the ability to use line of sight to communicate with another station at a given location does not change much over periods of minutes, hours, days, months, years, etc. Despite this, HF is not a very good choice for line of sight communications and there are several reasons why HF is not commonly used for line of sight communications. First, the lower frequencies HF generally require larger antennas and the available bandwidth in the HF range is somewhat limited. In addition, there also tends to be much more noise at HF compared to higher frequencies. This can be a problem because the limited bandwidth at HF usually means communications are carried out using AM or single-sideband modulation, which are much more sensitive to noise than (less bandwidth-efficient) FM. In practice therefore, most line of sight communications are carried out at VHF or higher, rather than at HF.

2.1.2 Ground wave

When there is no direct line of sight to another station, ground wave is a possible solution. Ground wave, sometimes also called “surface wave,” involves signals propagating along the surface of the Earth. Interaction between the lower part of the transmitted wavefront and the Earth’s surface cause the transmitted wave to tilt forward, allowing the signal to follow the curvature of the Earth, sometimes well beyond line of sight. Ground wave propagation is however highly dependent on two different factors: the conductivity of the

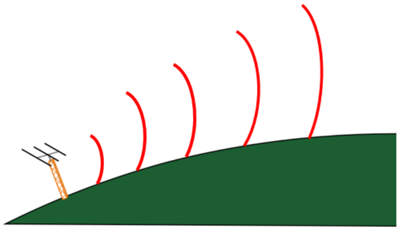


Figure 3 - Ground or surface wave

ground or surface over which the signal is propagating and the frequency of the transmitted signal. In general, higher surface conductivity provides better results in the form of greater distances that can be covered. Salt water has excellent conductivity, especially compared to dry or rocky land, so "ground" wave is a good choice for communication over water, such as ship-to-ship or ship-to-shore communications. With regards to frequency, ground wave propagation provides better results at lower frequencies. For example, the theoretical range of a 150 watt transmitter at 7 MHz is 35 kilometers over land, but close to 250 kilometers over the sea. At 30 MHz, however, the range falls to only 13 kilometers over land and just over 100 kilometers over salt water.

2.1.3 Skywave

The most commonly-used propagation mode of HF is skywave. Although ground wave and even line of sight HF propagation can allow for communication beyond line of sight (the latter due to diffraction), truly global communications at HF requires the use of skywave propagation. In skywave, layers of ionized particles in the Earth's upper atmosphere refract HF signals back towards Earth, allowing communications over many thousands of kilometers. The distances that can be covered by different frequencies are almost entirely a function of the altitude and density of different layers of ionized particles, collectively referred to as the ionosphere. Understanding HF propagation therefore requires an understanding of the different layers of the ionosphere, how the ionosphere is affected by the sun, and how the current state of ionosphere is quantified and the future state of the ionosphere is predicted.

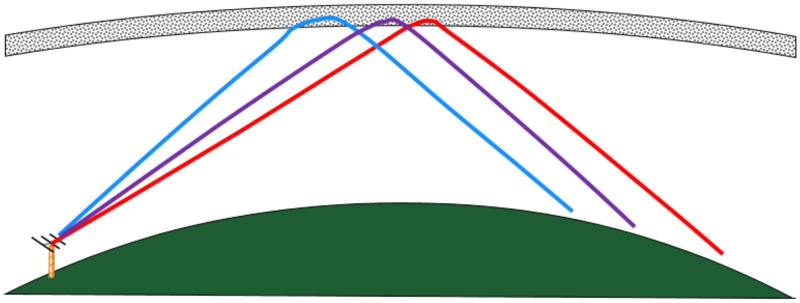


Figure 4 - Skywave (ionospheric) propagation

2.2 The ionosphere and skywave propagation

2.2.1 About atmospheric ionization

Ionization in the upper layers of the Earth's atmosphere occurs when ultraviolet energy and other forms of radiation from the sun strike gaseous atoms or molecules. This transfer of energy can cause electrons to become detached, resulting in a positive ion and, more importantly for the purposes of propagation, a free electron. These free electrons are held roughly in place by the Earth’s magnetic field. Generally speaking, the level of ionization and the number of free electrons increases as the amount of sunlight striking a given part of the atmosphere increases. When that part of atmosphere rotates away from the sun, that is, at night, this ionizing energy is removed and the ions recombine into electrically neutral atoms. Recombination is a slower process than ionization, meaning that atmospheric ionization increases rapidly at dawn, but decreases less rapidly at dusk.

2.2.2 About the ionosphere

The region of Earth’s atmosphere that undergoes this ionization lies above the stratosphere and is collectively called the “ionosphere.” The level or density of ionization in the ionosphere is different at different altitudes, and areas with ionization peaks are commonly grouped into so-called “layers” or “regions.” The ionospheric layers that are important for HF propagation are the D-layer (altitude: 60 to 100 km); the E-layer (altitude 100 to 125 km); and the F-layer, or layers, (altitude 200 to 275 km). These altitudes are not standardized and represent only approximate numbers – the “thickness” and “altitude” of ionospheric layers is never constant and at any given time will be different at different spots around the globe. The reason for defining these different “layers” is that each of these layers will refract and/or absorb HF signals in different ways.

One common misconception is that the ionosphere "reflects" signals. Radio frequency signals, including those at HF, can be reflected by dense or radio-opaque objects, but the mechanism by which signals are returned to Earth from the ionosphere is refraction. Like other forms of refraction, it is a difference in density at different layers (in this case, electron density) that makes this refraction possible.

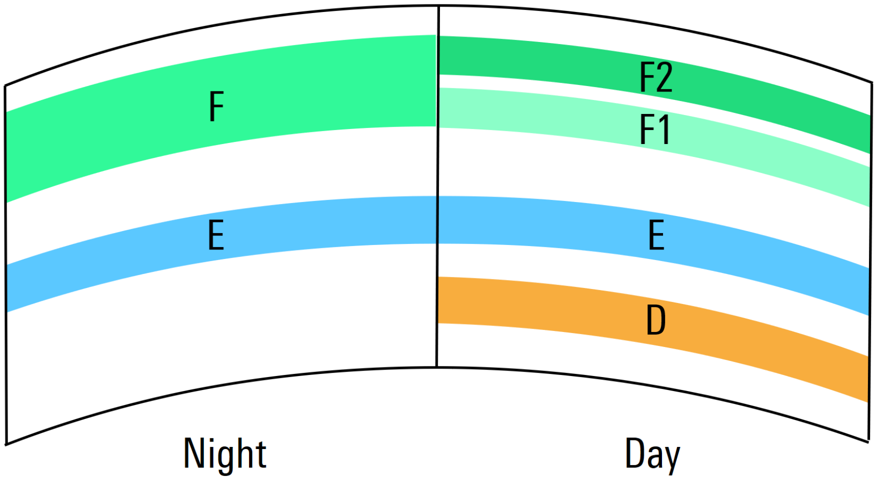


Figure 5 - Layers of the ionosphere

2.2.3 D-layer

The D-layer is the lowest level of the ionosphere. This layer only exists during daytime hours and disappears at night. Although the D-layer is ionized by solar radiation, the density of free electrons in the D-layer is too low to effectively refract HF signals and therefore the D-layer cannot be used for skywave propagation. In fact, the D-layer acts rather as an absorber of HF signals under most circumstances. This absorption is higher for lower frequency signals and increases with increasing ionization, so D-layer absorption is usually highest at midday. Due to this frequency-specific nature of D-layer absorption, higher frequency HF signals are a better choice during the daytime, whereas lower frequency signals work better at night, after the D-layer has disappeared.

2.2.4 E-layer

The next highest layer, the E-layer, is the lowest layer of the ionosphere that is capable of refracting HF signals back towards the Earth and is the lowest layer that supports skywave propagation. Compared to the other layers, the E-layer is relatively thin, with a typical width of approximately 10 km. The E-layer is much more “dense,” that is, ionized, during daylight hours, but unlike the D-layer it does not completely disappear at night. However, aside from mostly short-range, daytime communications and a few other special cases, E-layer propagation is not commonly used in HF.

As an aside, the E-layer is very important for propagation at **VHF** frequencies because it supports some rather exotic propagation modes, such as sporadic-E, that make long-distance communication over thousands of kilometers possible even at the relatively high frequencies of VHF.

2.2.5 F-layer

The F layer is the most important ionospheric layer for HF skywave propagation. During the day, the F-layer splits into two sub-layers, F1, and F2, which then merge back into a single layer again at night. Compared to the D and E layers, the height of the F layer(s) changes considerably based on things such as time of day, season, and solar conditions. The lower F1-layer primarily supports short- to medium-distance communications, but only during daylight hours. The F2 layer, on the other hand, is present more or less around the clock. This layer has the highest altitude and the highest ionization of all the layers, and therefore is responsible for the vast majority of long-distance HF communications.

2.2.6 MUF and LUF

The degree to which the different layers of the ionosphere refract and/or absorb radio frequency signals is largely a function of the signal's frequency. The general rule for HF skywave communications is to always use the highest possible frequency that will reach a given station or destination. This is called the **maximum usable frequency (MUF)**. By definition, signals whose frequencies are higher than the MUF will not be refracted by the ionosphere. For the most part, the MUF increases with increasing atmospheric ionization. Another important frequency threshold is something the **lowest usable frequency (LUF)**. When the signal frequency is at or below the LUF, communication becomes difficult or impossible due to signal loss or attenuation. Therefore, HF communications using skywave propagation is only possible when the transmit frequency is between the LUF and MUF. If the LUF becomes greater than the MUF, no HF communication is possible.

There is one very important difference between MUF and LUF. Because the LUF is mostly determined by noise, the LUF can be improved (lowered) by using higher transmit powers, better antennas, etc. MUF, on the other hand, is entirely a function of the ionosphere . The MUF cannot be improved (increased) by using more power or a better antenna.

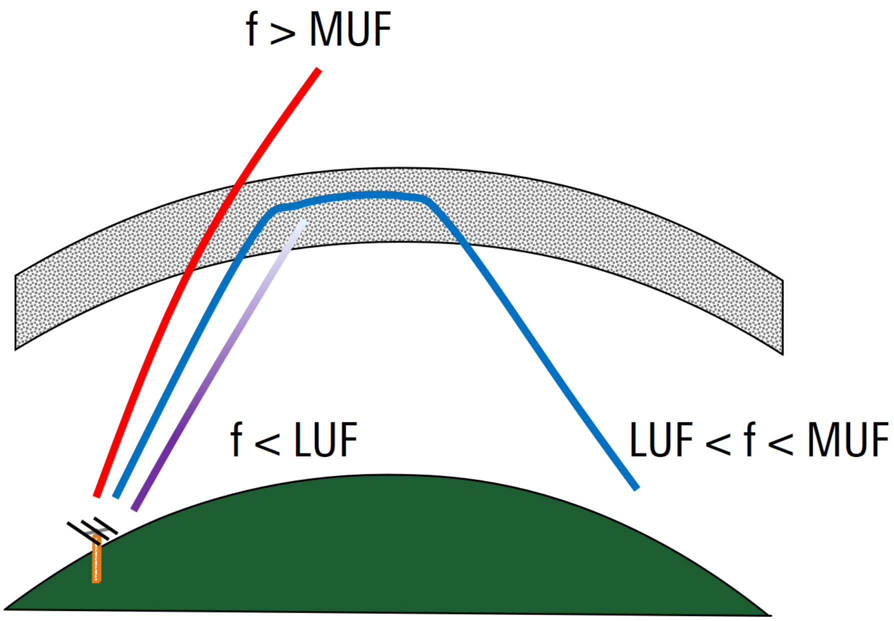


Figure 6 - Maximum and lowest usable frequencies

2.2.7 Critical frequency

One way to determine the MUF is purely through experimentation, but there are also methods for estimating the MUF using something called the **critical frequency**. The process for measuring the critical frequency is as follows: pulses at various frequencies are transmitted vertically by equipment called ionosondes. Depending on the frequency of the pulse, these pulses are returned by different layers of the ionosphere and the return time can be used to estimate the heights of the different ionospheric layers. Once a certain frequency is reached, the pulses are not returned by the ionosphere and instead continue on into space – this frequency is the critical frequency.

Critical frequency is a function of both the current ionization level as well as the measurement location, and is measured regularly at hundreds of locations around the world. Mathematically speaking, the maximum usable frequency is the critical frequency divided the cosine of the angle of incidence: if we send a signal straight up at 90 degrees, MUF and critical frequency are the same. But as a practical matter, the maximum usable frequency is usually estimated at 3 to 5 times the critical frequency.

2.3 Quantifying the ionosphere

Critical frequency is one way of quantifying the state of the ionosphere, but measuring critical frequency requires an active test: signals are transmitted and the returned signals are measured. In addition to critical frequency, there are three common passive methods that are used to quantify the state of the ionosphere. The first of these is sunspot numbers, which can be used to predict the level of atmospheric ionization. The second is the solar flux index, which is an actual measurement of the level of solar radiation. There are also two geomagnetic indices – the A index and the K index – which give an indication of the impact of solar particles on the Earth's magnetic field. Taken together, these quantities provide a good indication of the current state of the ionosphere and can be used to predict HF propagation.

2.3.1 Sunspot number

Sunspots are relatively cooler surface regions of the sun. They have temperatures around 3000°K versus the normal 6000°K seen elsewhere on the surface of the sun and last between a few days and a few months. Sunspots are associated with powerful magnetic fields and these fields affect how much radiation is given off by the sun: the greater the number of sunspots, the higher the levels of solar activity and radiation. Because of this, more sunspots generally means higher atmospheric ionization, a higher MUF, and overall better HF propagation.

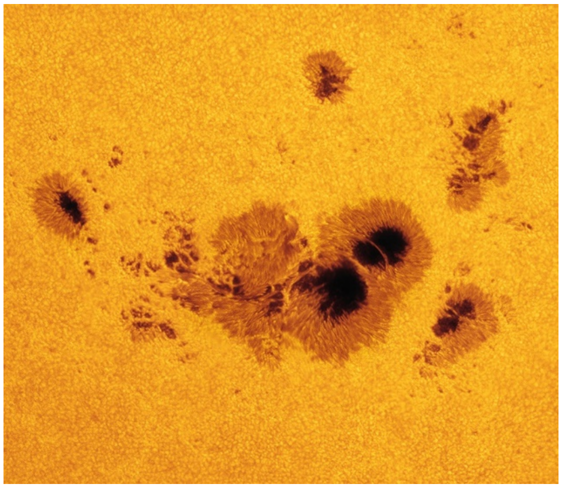


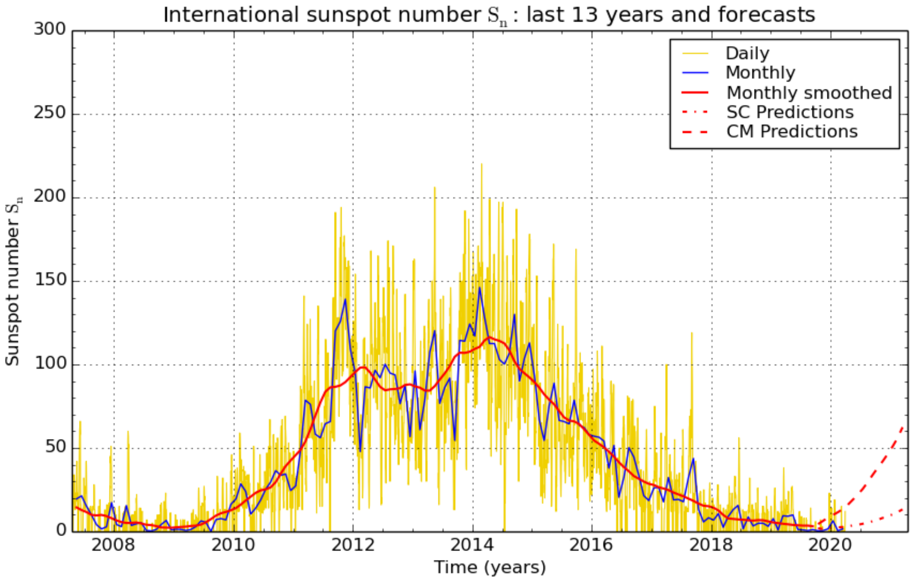
Figure 7 - Sunspots

The quantitative measure of sunspots is sunspot number, which is a daily measurement of sunspots. Note however, that sunspot number is not simply a count of the number of sunspots – it also takes into account additional factors such as the size and grouping of sunspots. Sunspot number is recorded by a number of solar observatories around the world, and sunspot number values range from zero to a maximum recorded value of 250. Sunspot data has been collected for almost 400 years, providing valuable information on how the number of sunspots changes over time.

2.3.2 Sunspot or solar cycle

And sunspot numbers do change over time. In fact, sunspot activity follows a roughly 11 year solar or sunspot cycle, during which times the sunspot number increases and decreases. Generally speaking, sunspot numbers are usually around 150 at the peak of a cycle, during which time HF propagation is very good on most frequencies, including higher frequencies. At the bottom or "trough" of the sunspot cycle, sunspot number is close to zero, meaning much poorer HF propagation.

Given the period of the sunspot cycle, it should be clear that sunspot cycle is primarily used for long-term predictions of HF propagation – that is, in terms of years – and over this time period it is fairly reliable. It should however be noted that at several points in history, for example, in the late 1600s and the early 1800s, sunspot number stayed low for several decades, created so-called “minimums” with very little solar activity. The reasons for this are still very much a mystery.



SILSO graphics (http://sidc.be/silso) Royal Observatory of Belgium 2020 April 2

Figure 8 - Sunspot numbers and the solar cycle

2.3.3 Solar flux index

Solar activity can also be quantified by measuring the level of solar noise, or “flux,” at a frequency of 2800 MHz. These measurements are reported as the solar flux index, with values given in so-called solar flux units (s.f.u.). Measured solar flux values generally fall in the range of approximately 50 during a solar cycle minimum to near 300 during a solar cycle maximum. Since solar flux is a measurement, not an observation, it tends to be more consistent and reliable than sunspot number, but solar flux index also does not have a 400 year history of values. Solar flux values tend to correlate quite well with sunspot numbers. Like sunspot number, higher values of solar flux mean a higher maximum usable frequency and better HF propagation.

2.4 Ionospheric disturbances

2.4.1 Solar flares

Sunspot number and solar flux index are valuable measures of longer-term variations in solar radiation. The ionosphere is also affected by shorter duration events occurring on the sun. The most important of these are solar flares, which are a type of eruption on the surface of the sun. Solar flares cause a rapid rise in both X-ray and ultraviolet radiation as well as the ejection of both low- and high-energy particles. Solar flares are essentially unpredictable, but do occur more commonly during peaks in the 11 year sunspot cycles. Solar flares have a significant effect on HF propagation, because they can lead to sudden ionospheric disturbances, polar cap absorption, as well as both geomagnetic and ionospheric storms.

2.4.2 Sudden ionospheric disturbances

As the name implies, a sudden ionospheric disturbance (SID) is an unexpected event caused by the arrival of large amounts of solar radiation. A SID occurs about eight and a half minutes after the emergence of a solar flare, that is, at the same time the flare becomes visibly detectable on the Earth. This radiation causes strong D-layer ionization, which in turn causes D-layer absorption to increase rapidly, starting at the lower frequencies and moving upwards. The affected frequencies are often almost completely blacked out. Fortunately, a sudden ionospheric disturbance only impacts the sunlight hemisphere and tends to last a relatively short time, typically about an hour or so. And in some cases, smaller solar flares actually can enhance HF propagation by increasing ionization at higher frequencies without a corresponding increase in D-layer absorption.

2.4.3 Polar cap absorption

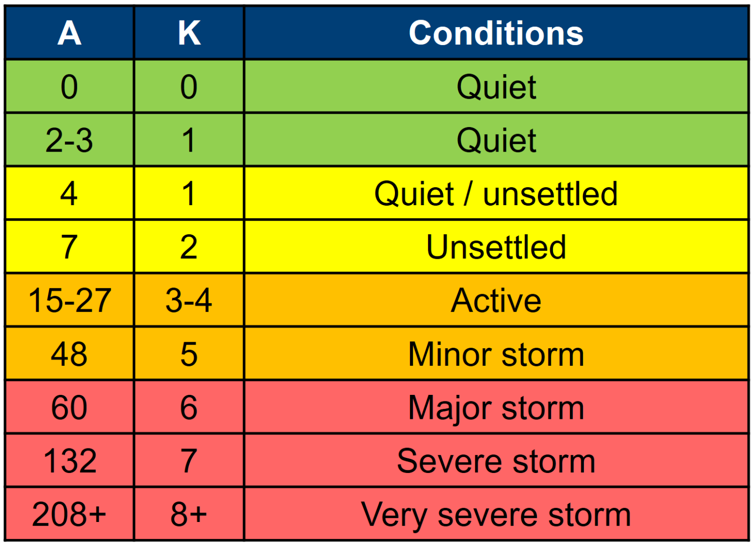
The next effect of a solar flare is polar cap absorption. The high energy particles emitted by a flare reach the Earth several hours later, and the Earth’s magnetic field prevents them from entering except at the poles. Once these particles enter the atmosphere, they can increase D-layer absorption in the polar regions and this effect can last for several days. During this time, HF signals traveling through or near the poles will be blocked by the increased attenuation, but paths that do not go near the poles may remain relatively unaffected during this event.

2.4.4 Geomagnetic and ionospheric storms

Geomagnetic storms are caused by lower-energy particles arriving at the Earth. This occurs 20-40 hours after a solar flare. These particles can also be generated during an event called a **coronal mass ejection (CME)**, which can occur independently of a solar flare. In either case, these particles can cause geomagnetic storms. Geomagnetic storms are responsible for creating visible aurora in higher latitudes, but can also can interfere with GPS signals, satellites in general, terrestrial power distribution networks, etc. Geomagnetic storms do not directly impact HF propagation, but the presence of a geomagnetic storm can create an ionospheric storm. Ionospheric storms lower the maximum usable frequency and degrade HF propagation. As noted earlier, if the MUF becomes lower than the LUF, an ionospheric storm can create a complete HF skywave blackout. One final note: it is possible to have geomagnetic storm without an ionospheric storm, but the converse is not true – all ionospheric storms start out as geomagnetic storms.

2.4.5 A and K indices

Sunspot number and solar flux index are used to quantify ionospheric conditions, but to quantify geomagnetic conditions A and K indices are used. In general, lower values for A and K mean a more stable ionosphere. A and K are measured at observatories around the planet, and these local values can be averaged to produce the planetary values A_p and K_p. One of the biggest differences between these two indices is that A is calculated daily whereas K is measured every 3 hours. Higher values of K indicate a current or ongoing geomagnetic event, whereas A is useful for determining how long this disturbance has been occurring.



A	K	Conditions
0	0	Quiet
2-3	1	Quiet
4	1	Quiet / unsettled
7	2	Unsettled
15-27	3-4	Active
48	5	Minor storm
60	6	Major storm
132	7	Severe storm
208+	8+	Very severe storm

Figure 9 - A and K indices

3 HF Communications

3.1 HF in decline

For the first half of the 20th century, HF dominated global communications, but beginning in the late 1960s, satellites began replacing HF in several application areas. This trend accelerated rapidly over the next several decades for several reasons. Satellites can offer much higher data rates than was ever possible over HF, even under the best propagation conditions. Satellite communications are relatively immune to changes in propagation – this is in sharp contrast to the highly variable and somewhat unpredictable nature of ionospheric or skywave propagation at HF. Because of the more stable and straightforward nature of satellite signal propagation, satellite communications generally did not require highly trained or experienced operators for reliable communications.

Another important factor in the decline of HF was the growth of the Internet. The Internet "raised the bar" for global data connectivity by providing very high data rates and more or less instant global connectivity. The Internet also increased expectations with regards to availability – the Internet was “always on” and over time Internet access became more or less globally available, particularly in developed countries. The Internet could meet data needs over increasingly larger areas of the world, and where terrestrial internet was not available, satellite was an acceptable substitute.

During the last several decades, a decline in both interest in and use of HF created a corresponding decrease in awareness of and funding for HF. HF became something of a niche application: manufacturers provided only nominal (if any) support for HF in their products, and the pool of experiences HF developers and operators declined dramatically. Even in the amateur radio community, a traditional bastion of HF, a combination of lackluster solar cycles and the availability of inexpensive VHF handhelds moved the focus away from HF to more local communications.

3.2 Satellite vulnerabilities and weaknesses

Figure 10 - F-15 releasing an ASAT missile

Along with all of their benefits, satellites also suffer from a number of vulnerabilities or weaknesses. A hostile force can employ a wide variety of anti-satellite (ASAT) technologies designed to temporarily or permanently incapacitate a space vehicle. Ground based attacks, such as those using high-powered lasers, are relatively inexpensive and are difficult to stop or detect. These types of attacks can even be used by countries that have no launch capabilities of their own. For countries with launch capabilities, either ground-launched or air-launched weapons can be used to destroy satellites. The United States, the Soviet Union / Russia, and China have all carried out numerous ASAT tests and many other countries are developing ASAT capabilities. Jamming is another serious vulnerability, in part because satellites are generally not “frequency agile” and operate at frequencies which are relatively easy to jam. Additional threats to satellite communications include solar storms. The same solar flares and coronal mass ejections that caused problems in the ionosphere can disrupt satellite communications and have even been blamed for physical damage to satellites.

One should also bear in mind that satellites or satellite constellations do not always provide truly “global” coverage. For example, coverage in the polar regions has long been a weak spot for many satellite systems. Not all satellite constellations cover the poles and those that do, for example, Iridium, require a relatively large constellation to do so. There may even be gaps in satellite coverage in the middle of an ocean Furthermore, certain terrain or geographical issues can also present a challenge when it comes to satellite coverage. Mountainous regions or areas with significant foliage or canopies like jungles can block the direct line of sight needed for most satellite communications.

Latency is another concern when using satellites. Applications that make use of geosynchronous satellites must be able to deal with delays of approximately 250 ms due to the distances involved. One final concern is security: countries may not wish to rely on an ally's satellites for their own critical communications

3.3 The rebirth of HF

These vulnerabilities and weaknesses are not necessarily common events or issues, but as global connectivity has become more and more “mission critical,” there has been an increasing interest in providing a separate technology that can deliver similar global connectivity, even if this connectivity does not match the speed and bandwidth provided by satellites. This is a role that HF is well suited to play.

HF provides truly global coverage, including polar regions and regions that are “terrain-challenged.” Aside from satellites and HF, there few other technologies that can reliably provide connectivity between any two points on the planet. HF does not require a special infrastructure such as a constellation of expensive satellites with a limited useful life – the “infrastructure” for HF is the ionosphere. This lack of a man-made infrastructure substantially reduces the cost of using HF and also helps to make HF robust against attacks. Solar events may temporarily disrupt HF propagation, but there is no practical way for humans to damage, destroy, or deny use of the ionosphere. Because of the lower frequencies and frequency agility – so to speak – HF communications are much harder to jam compared to satellite.

However, in order to allow HF to meet the minimum requirements for a modern global communications technology, improvement or enhancements over “traditional” or “legacy” HF are required. The first and most important of these is improved data performance. Although HF will never match the throughput provided by satellites, a certain minimum data rate is necessary for making HF a viable choice in in modern applications. Despite the dominance of data, voice is still a critical component in a global communications system, and here too there is substantial room for improvement compared to “legacy” analog HF voice. With regards to propagation, there is little that can be done to change the nature of ionospheric or skywave propagation, but the availability and reliability of the this medium can be improved by means of modern advancements in modulation and error detection / correction. Lastly, ease of operation over HF can be improved by simplifying the process of selecting a frequency or path and automating the process by which connections are established and maintained or modified.

3.4 Improving availability and operation

Figure 11 - Portable HF operation in the field

The first and most fundamental task when using HF for global communications is deciding which frequency should be used to reach a given station or geographical location. This is largely a function of the state of the ionosphere, which in turn is a function of time of day, period in the solar cycle, and any unusual ionospheric conditions. In legacy HF communications, skilled human operators could usually estimate the maximum usable frequency, choose the most appropriate antenna type and/or orientation, etc. based solely on their training and experience. In more recent decades, propagation prediction tools such as VOACAP could be used to augment an experienced operator's judgement or help less experienced operators determine the best frequency. If conditions changed, for example, due to changing propagation or interference/jamming, a human operator would recognize this and intervene, usually by changing output power or frequency. Clearly this approach does not scale and is very operator-dependent. The more modern approach therefore attempts to handle all of these functions automatically. This is sometimes referred to as "adaptive HF", which is outlined in ITU-R F 1110-2 1. In adaptive HF, the optimum frequency is selected automatically, the initial communication is established automatically, and the system automatically adapts to changing propagation or congestion/ interference if needed. By far the most common way that these general principles are implemented is through **automatic link establishment (ALE)**.

3.5 Automatic link establishment

In ALE, all stations are assigned an address and that address (or various types of group addresses) is used when calling a given station. Stations scan predefined lists of channels or frequencies, and if a station hears itself being called on one of these channels, it then attempts to synchronize with the calling station. The frequencies that are used when trying to call a given station are ranked based on **link quality analysis (LQA)**. Stations periodically transmit their address along with a sounding signal. Stations which are currently scanning their list of channels measure the received signal and record this value along with the date, time, and address of the transmitting station. These measurement values are used to build up a database that can be used when picking a channel for calling a given station. Another useful feature of ALE is the ability to listen to a channel to see if it is already in use (occupancy detection) and the ability to adapt to changing conditions.

First generation ALE systems date back to the late 1970s and early 1980s. These systems were proprietary and therefore were not interoperable. By the mid-1980s, the need for interoperability and more advanced features had grown such that a new second generation (2G) of ALE was standardized as MIL-STD-188-141A in 1986. This second generation of ALE was interoperable and helped promote more widespread use of ALE. ALE became so popular that a third generation (3G) was developed and standardized a little over a decade later. Third generation ALE was a substantial step forward in that it supports faster link setup and more reliable setup under noisy conditions, that is, when SNR is low. 3G ALE supports more efficient allocation of spectrum, allowing more users to share the very limited bandwidth at HF, and is also more scalable in terms of the number of stations that can be supported.

3.6 Legacy HF modulation

Traditionally, bandwidth on HF was allocated as 3 kHz "channels." The reason for this particular channel width of 3 kHz is to support the most common traditional use of HF transmission, namely, single-sideband (SSB) voice. In older or legacy HF systems, various types of modems could be used to transmit data over voice channels, that is, within the same 3 kHz bandwidth that was used for voice. There are a very large number of different modulation schemes that have been used to transmit data over HF, many of which are no longer in use. In the earlier days of HF communications frequency shift keying (FSK), was the most common modulation scheme, and more recently phase shift keying (PSK) is also widely used. These were followed so-called "M-ary" modes like MFSK, in which the number of symbols or states was increased to provide greater throughput. More recently, there has been a steady increase in even higher-throughput modulation schemes such as variants of (higher-order) QAM, or quadrature amplitude modulation. Even voice has undergone a transformation, with modernized HF systems often sending voice digitally over data channels. This has the potential for providing much higher quality than traditional analog voice, especially under challenging channel conditions.

3.7 Improving HF bit error rate

It would not be an exaggeration to say that HF is one of the worst possible transport media for sending digital data, or "bits." HF is noisy and variable, and both slow and rapid fading are common. Often errors come in the form of burst errors, where many bits in a row are corrupted by bursts of noise or sudden fades. In legacy HF and prior to modern computational resources, it was not easy to either detect or correct bit errors, and this in turn limited maximum transmission speeds.

Modern computing resources have allowed significant improvements in dealing with bit errors. Burst errors can be minimized by using **interleaving** to "spread out" these errors over a larger number of bits. Interleaving greatly improves the efficiency of another technique called **forward error correction (FEC).** FEC adds additional bits to the transmitted data which can detect and correct single bit errors at the receiver. For those cases when errors are uncorrectable, a higher-layer process called **automatic repeat request (ARQ)** is used to request retransmission at the packet level. Although these techniques may seem somewhat mundane (in part because they have been used in other digital communications for many years), the application of these techniques in HF data communications has been critical in improving of HF data throughput and reliability.

3.8 Wideband HF

Increasing bandwidth is key to increasing throughput. Some early attempts at improving on the standard 3 kHz HF channel involved using additional, independent sidebands. Although the use of multiple smaller channels does increase throughput, the use of a single larger channel can provide better performance, and this is the reason for the development of **wideband HF**. The most important current standard for wideband HF is MIL-STD-188-110D, updated in 2017. This standard defines contiguous bandwidths of up to 48 kHz in various steps, allowing the waveform to be adapted to available spectrum. Data rates of up to 240 kilobits per second have been achieved on a 48 kHz channel.

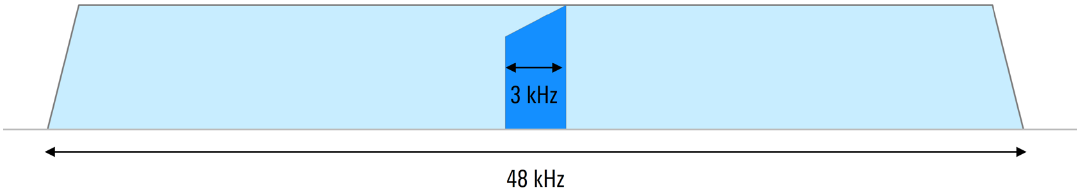


Figure 12 - Narrowband versus wideband HF

Another advantage of this wider waveform is increased robustness in hostile environments. A wider signal is harder to detect because the energy is spread over a larger bandwidth and wider signals are also more resistant to jamming attacks

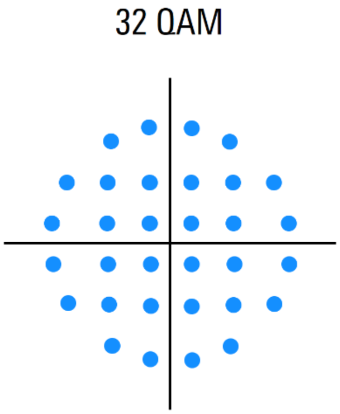


Figure 13 - Wideband HF 32 QAM constellation

Wideband HF also includes improvements in modulation types and error reduction methods such as FEC and interleaving. Of particular interest are the modulation types specified for wideband HF. In addition to traditional or standard PSK, specially-designed QAM variants are included. These variants have modulation orders up to 256 QAM, since higher modulation order enables higher throughput. Of special interest is the fact that these constellations have a somewhat "circular" shape, as opposed to the more “square” QAM constellations seen in most other applications. These circular constellations have the advantage of reducing the peak to average ratio of the signal, which in turn simplifies both the design and efficiency of radios and amplifiers.

The ability to use wideband HF does of course require the availability of larger contiguous regions of unoccupied spectrum. These available bandwidths or "channels" may be limited by regulations, other users (licensed or otherwise), noise, jamming, interference, etc. In addition, regulatory authorities may also prohibit the use of wideband HF by certain categories of users or in certain frequency ranges or bands. For example, United States Federal Communications Commission regulations (Title 47 CFR Part 97) prohibit the use of wideband HF in the amateur radio bands.

3.9 Fourth generation ALE

The development of fourth generation (4G) or wideband ALE is largely driven by the rollout of wideband HF. Because wideband HF supports different bandwidths, modulation types, error detection / correction parameters, etc. 4G ALE is a critical component in ensuring that stations are able to exchange capabilities, intended traffic type, etc. and negotiate the most efficient parameters for a given connection. Building on previous versions of ALE, 4G ALE also supports more advanced forms of spectrum sensing for determining the optimal frequency and bandwidth for a given connection, and for avoiding interferers. Furthermore, 4G ALE greatly reduces the amount of time needed to set up a link and allows easier and more efficient sharing of channels with other stations. All of these features enable reliable, automated systems.

4 Summary

Global HF communications are almost entirely based on skywave propagation rather than direct line of sight or ground wave propagation. In skywave, signals are refracted by the ionosphere, although the effect of some layers is more to absorb signals than to refract them. Whether or not a signal is refracted or absorbed by the ionosphere is largely a function of the frequency of the signal and the amount of ionization in the upper atmosphere. This ionization increases during daylight hours while the sun is illuminating that side of the Earth. On a larger time scale. ionization also increases as the number of sunspots increases, with the number of sunspots following a roughly 11-year solar cycle. Aside from these semi-regular effects, certain types of solar events can unexpectedly or unpredictably disrupt the ionosphere and hence HF propagation. Solar flares are the most common of these, and flares can lead to so-called sudden ionospheric disturbances, polar cap absorption, and both geomagnetic and ionospheric storms. A coronal mass ejection is a less common, but often more severe, source of geomagnetic storms. Using measurements such as sunspot number, solar flux index, and the A and K indices allow the current state of the ionosphere to be quantified and/or predictions to be made regarding future HF propagation conditions.

Satellites largely replaced legacy HF for global communications beginning around the 1970s and the dominance of satellites continues to this day. Satellites provide much higher throughput than HF links, and satellite communications are not subject to variable and somewhat unpredictable propagation. Satellite systems are generally much easier to use than legacy HF systems that require highly skilled or experienced operators to establish and maintain communications.

Despite these clear advantages, satellites are expensive and are vulnerable to a variety of attacks. In some cases satellites are unable to provide complete global coverage. In light of the mission-critical nature of global data communications, there is a strong consensus with regards to the need for an alternative or redundant global data communications system. Recent technological advancements, in particular ALE and wideband HF, have reduced or eliminated many of the traditional shortcomings associated with skywave propagation and have helped to bring about a renewed interest or "rebirth" in the use of HF.

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