SPACE WEATHER IMPACTS on GNSS

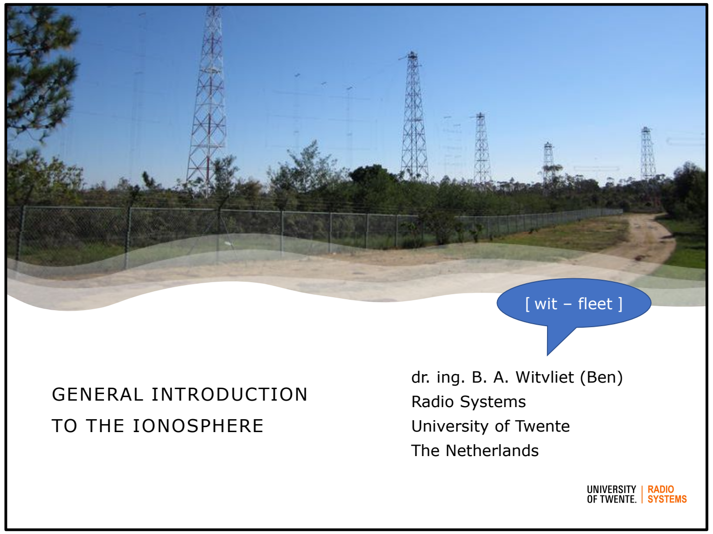
SWIC

Collaboration of

Solar-Terrestrial Centre of Excellence

UNIVERSITY OF TWENTE. | RADIO SYSTEMS

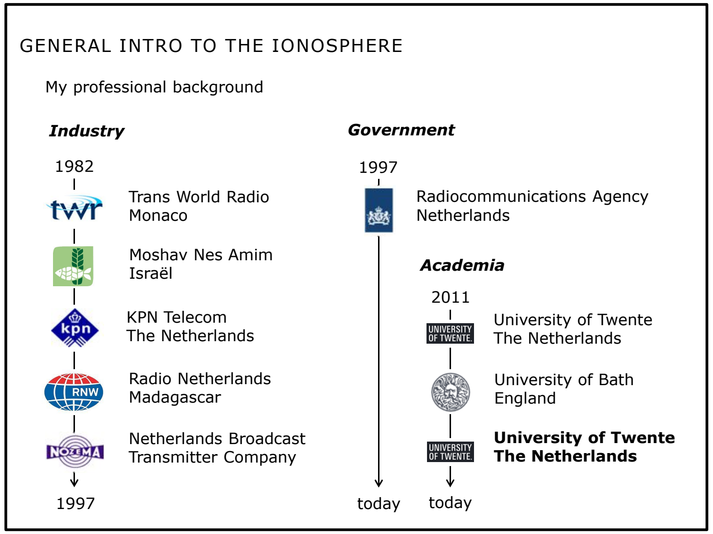
Koninklijk Nederlands Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu



My name is Ben Witvliet [pronounce "wit-fleet"].

I work as a researcher in the Radio Systems group of the University of Twente.
I do research on HF (ionospheric) radio for humanitarian applications.

This photo shows the Radio Netherlands Madagascar radio relay station, where I was the Chief Engineer.



My professional background is in broadcasting and spectrum management.

I also work as a technical advisor for the Radiocommunications Agency of The Netherlands,
doing international work in the International Telecommunication Union (ITU) and the European Telecommunication Standardization Institute (ETSI).

GENERAL INTRO TO THE IONOSPHERE

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We can discuss in English, Dutch, German and French
(English preferred)

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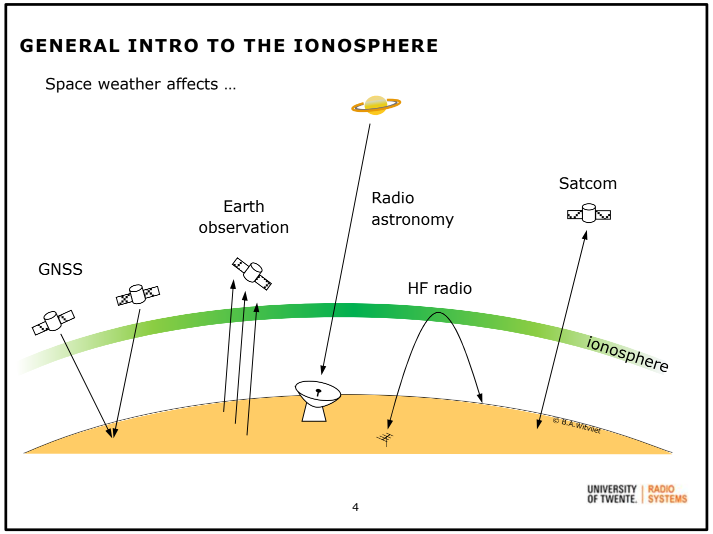
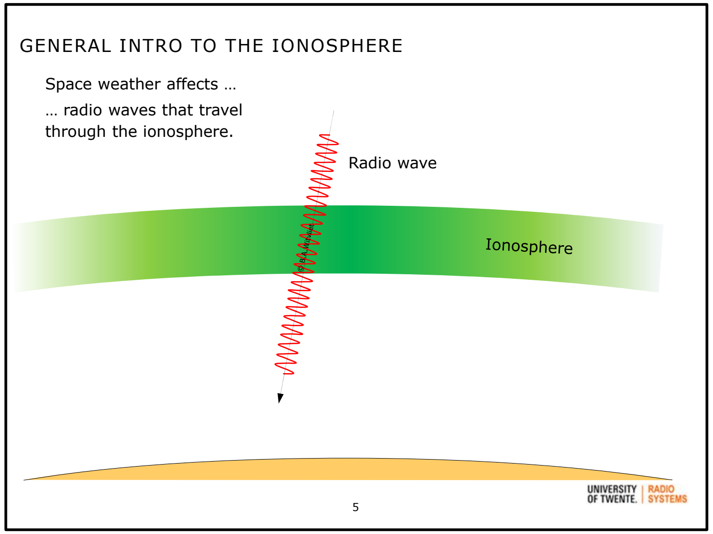
For questions and information, you can always reach me via email b.a.witvliet@utwente.nl or by phone +31 6 1219 0688. We can discuss in German, French, English and Dutch. My vocabulary is best in the latter two.

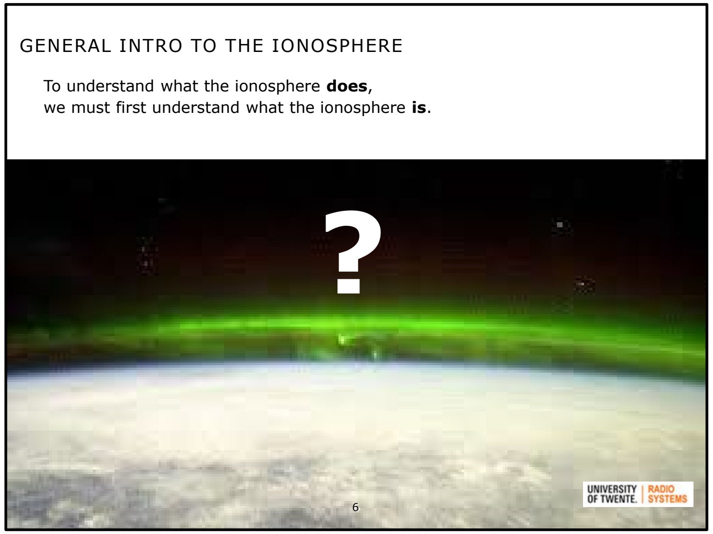


Space weather affects

- » GNSS navigation Earth observation
- » Radio astronomy
- » HF radio communication
- » Satcom (satellite communication)

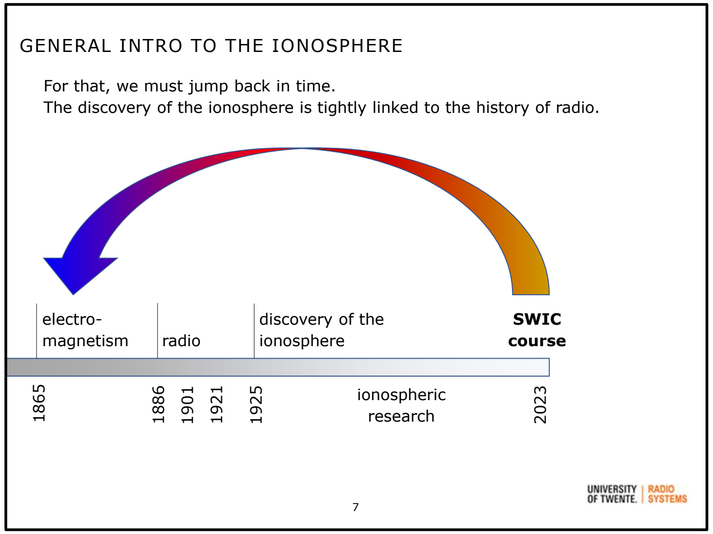


Common denominator:
All these services make use of radio waves that travel through the ionosphere.



To understand what the ionosphere does that affects these radio waves, we must first understand what the ionosphere is.

The picture shows the ‘Northern Lights’, seen from the International Space Station. The aurora makes the ionosphere visible to us.
Picture courtesy of NASA.



For that we must jump back to early years of radio.
Because the discovery of the ionosphere is tightly linked to the history of radio.

GENERAL INTRO TO THE IONOSPHERE

Obviously, to do that, we need a fast car …

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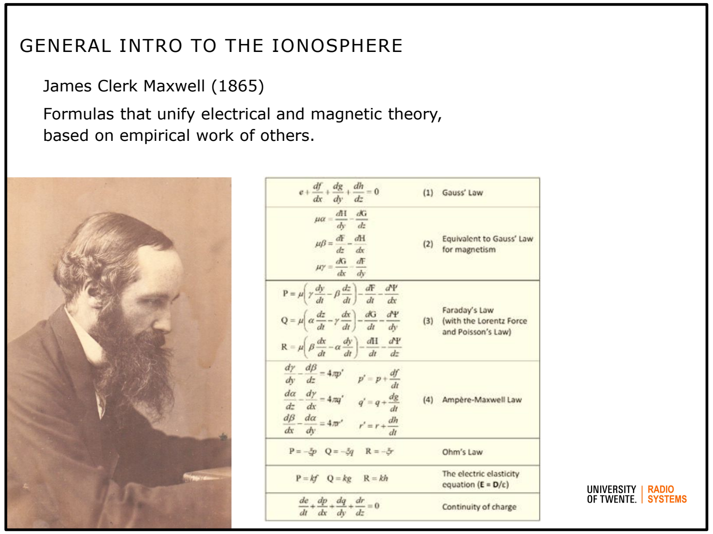
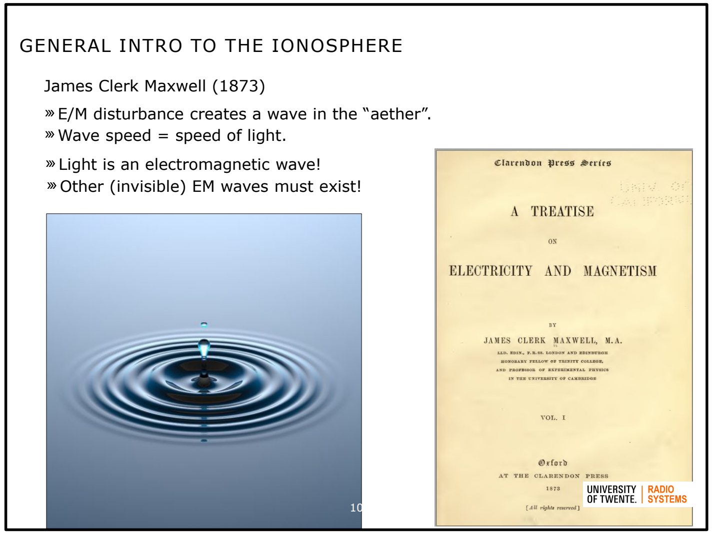
So, we - obviously - we need a fast car and a weird professor... ☺



In 1865, Scottish prof. James Clerk Maxwell publishes an integral set of formulas that describes all known electric and magnetic phenomena.
He builds on empirical work from other scholars such as Lorenz, Ohm, Gauss, Coulomb, Ampère, and Faraday.

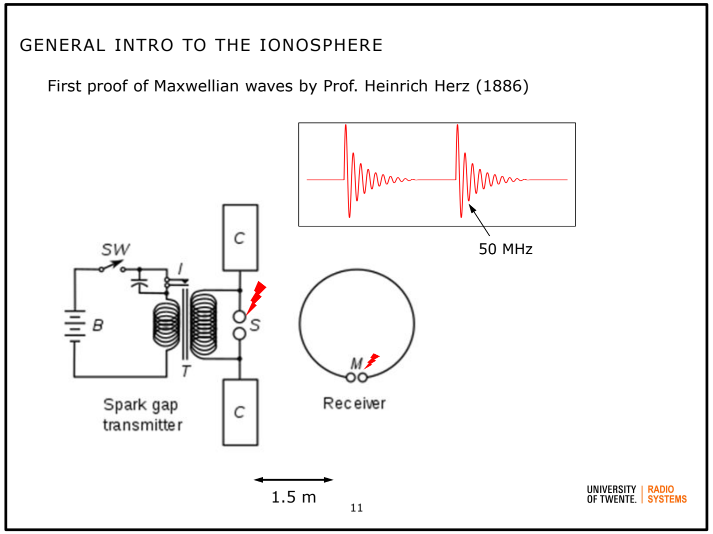
Pictures courtesy of [unknown source]



Maxwell also shows (in 1973) that a disturbance in the electric or magnetic field leads to electromagnetic waves. He calculates the speed of these waves. Seeing that the speed of these waves equals the speed of light - which was measured precisely by Foucault in 1862 - he concludes that light must be an electromagnetic wave. This also implies that there must be other electromagnetic waves. Waves that we cannot see.

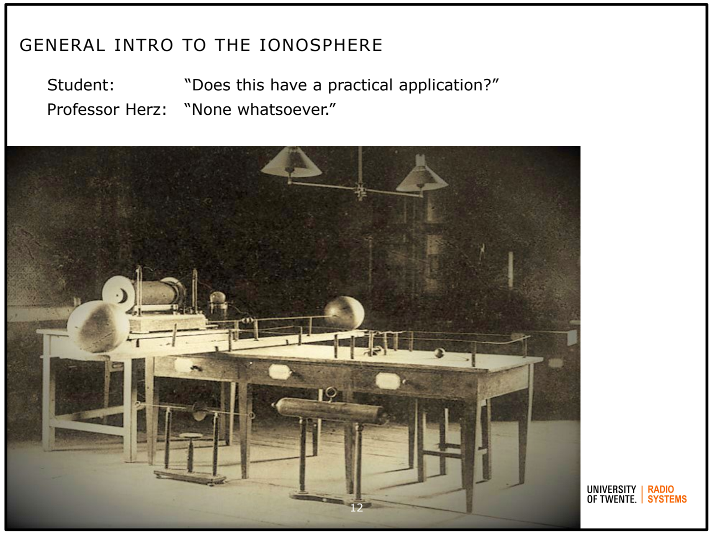
In his mind he still visualizes waves in a mechanical "aether" : something invisible, solid, and with infinite elasticity.

For further reading:
https://www.britannica.com/science/Yang-Mills-theory
https://www2.mathematik.tu-darmstadt.de/~bruhn/Original-MAXWELL.htm (in German)
https://en.wikipedia.org/wiki/Electromagnetic_wave_equation



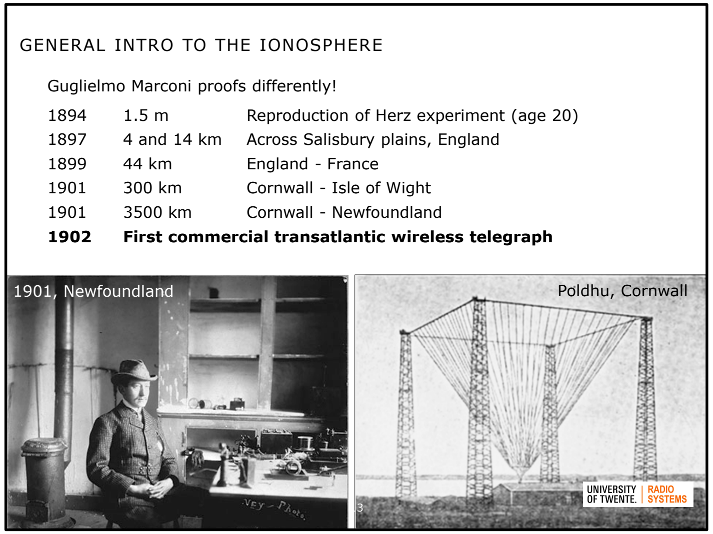
On 13 November 1886, Professor Heinrich Herz does an experiment to prove that these electromagnetic waves really existed. He creates a high frequency oscillator, using a battery, a spark gap and a resonant circuit of coils and capacitors. Every spark produces an oscillating current with a frequency of approximately 50 MHz.

At 1.5 meters distance he places a resonant loop antenna, again with a spark gap. The induced voltage in this loop antenna now produces tiny sparks, which can be seen when the room is darkened.



When he demonstrated this experiment to his students at the Technische Hochschule of Karlsruhe, one of them asks: “Is there a practical application for this phenomenon?”
On which Herz answers: “None whatsoever.”

Picture Heinrich Herz’s experiment, copyright of Deutsches Museum, BN49939, reproduced with permission.
Material for further reading:
https://wearebroadcasters.com/radio100/moments/72.asp#:~:text=In%201888%2C%20German%20physicist%20Heinrich,gap%20on%20a%20receiving%20antenna.



He is proven wrong by Guglielmo Marconi, of Pontecchio, near Bologna, in Italy. This son of rich parents sees the potential of Herz's experiment. He wants to create a "wireless telegraph‟.
In 1894 he reproduces the experiment of Herz. He improves the antenna and detector, and later also makes the receiver and transmitter frequency selective. This gradually increases the distance between transmitter and receiver.

1894	1.5 m	Reproduction of Herz experiment
1897	14 km	Across Salisbury plain, England
1899	44 km	England to France
1901	300 km	Cornwall to Isle of Wight
1901	3500 km	Transatlantic test, Cornwall to Newfoundland (25 kW)

As people doubt his achievement, he organizes recorded reception with witness statements on the S.S. Philadelphia of the American line, with reception up to 2100 km, in 1902.

In 1902 he starts a commercial radiotelegraph service between England and America. The wavelengths he transmits on is around 4000 meters, at a frequency of 750 kHz. He also installs radio stations on ships. The radio operators are called 'Marconists'.

First Picture: Guglielmo Marconi and his instrument inside Cabot Tower, Signal Hill, St. John's, Newfoundland, Canada. Photo taken on 12 December 1901, the day he demonstrated sending a wireless signal across the Atlantic Ocean.
Credit: Library and Archives Canada/C-005945, used with permission.
Second picture: Antenna in Poldhu, Cornwall. Credit Alamy Stockphotos, used with permission.

For further reading the Nobel Prize lecture of Marconi in 1909 can be found here:
https://www.nobelprize.org/prizes/physics/1909/marconi/lecture/
And the story of the radio station on board of the Titanic in 1912:
https://revolutionsincommunication.com/features/radio-and-the-titanic/

GENERAL INTRO TO THE IONOSPHERE

Many high-power transmitters soon interconnect the world.
Long wavelengths: 1000 to 20,000 meters.

200 kW electro-mechanical transmitter at 17.5 kHz in Grimeton, Sweden.

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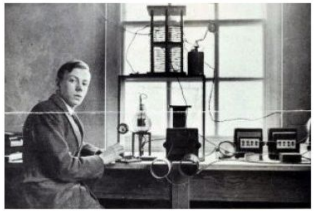
The invention of Marconi changes the world. Gradually, the world is interconnected by large transmitters, wielding powers of 100 kW to 1200 kW, with antennas of several km length. These transmissions use long wavelengths, from 1000 meters to 20 km, using frequencies from 15 to 300 kHz.
During World War I, these radio links with the colonies become politically important, as over-land telegraph lines can be cut.

Picture from the 200 kW Alexanderson electro-mechanical transmitter at 17.2 kHz, courtesy of the Alexanderson Association. This station is kept as a museum and is still fully operational.
https://alexander.n.se/en/the-radio-station-saq-grimeton/the-alexanderson-transmitter/

Radio amateurs flee to shorter wavelengths: 220 meters and 110 meters.
Surprisingly, short waves prove very efficient.



Cecil Goyder, G2SZ
Frank Bell, Z4AA

First trans-world radio contact
with only 50 Watts in 1924.

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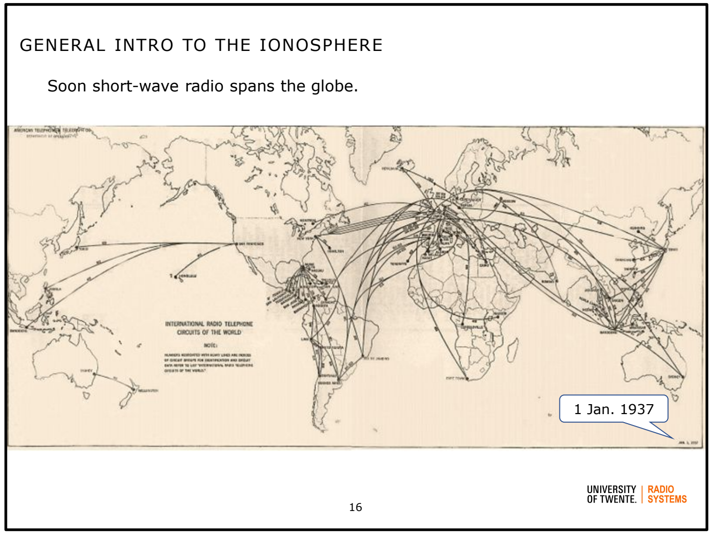
Marconi initially was just a radio amateur, a hobbyist. While Marconi creates a commercial company, many other continue experimenting, privately and without commercial interest. But wavelength longer than 1000 meters (300 kHz) are now crowded with high power commercial and governmental radio stations. And the harmonics of the powerful transmitters pollute wavelength up to 300 meters (1 MHz). Therefore, the radio amateurs seek refuge at shorter wavelengths.

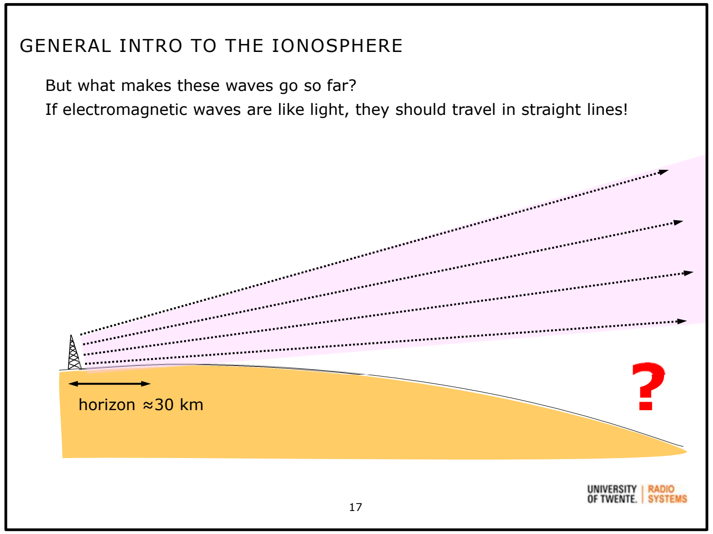
To their surprise, at these frequencies, radio wave propagation is very efficient! In 1921, during the first Atlantic test, 26 US radio amateurs are heard in Scotland, using a wavelength of 230 meters (1.3 MHz).
They use relatively low power, between 50 W and 1000 Watt. That is 100 to 1000 times less than the long wave transmitters!
In 1924, radio amateurs make the first radio contact to the other side of the world, between England and New Zealand. Power 50 W, wavelength 92 meters (3.3 MHz).

Pictures courtesy of [unknown source]

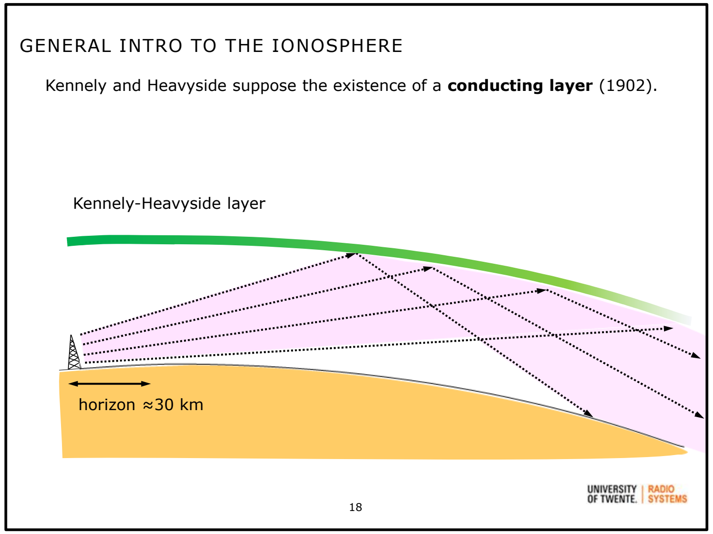


This brings international recognition for the radio amateurs. The International Telecommunication Union awards them with exclusive spectrum for experiments. The commercial operators now scramble to install equipment for the short waves, or High Frequency (HF) as we call it nowadays. When the spark transmitters are replaced by vacuum tube equipment, voice-over-radio becomes possible. In 1927, AT&T launches a telephone service between New York and Europe, extending telephone connections with ionospheric radio transmitters. This is revolutionary, as the sea cables have little bandwidth, and do not support voice. By 1937, the radio telephony network spans the globe. This remains so until the first communication satellites are launched (1965) and glass fibre ocean cables are installed.

Picture courtesy of Bown, R., Transoceanic radiotelephone development. Proceedings of the Institute of Radio Engineers, 25(9), 1937: pp.1124-1135.
For further reading: https://earlyradiohistory.us/sec011.htm

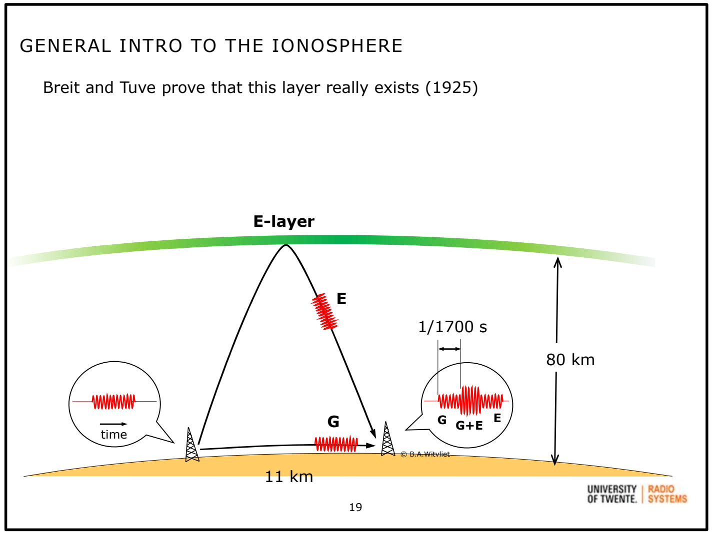


The success of the Marconi and amateur radio communication makes scientist wonder what mechanism is causing the waves to arrive beyond the horizon.
This is so different from the behavior of light, which strictly follows straight lines.



Already in 1902, to explain the over-the-horizon transmissions of Marconi, Arthur Kennely and Oliver Heavyside supposed a conducting layer high up in the atmosphere.
Others – rightfully so – assumed that the long waves sticked to the earth due to ground conductivity, so-called ground-waves.

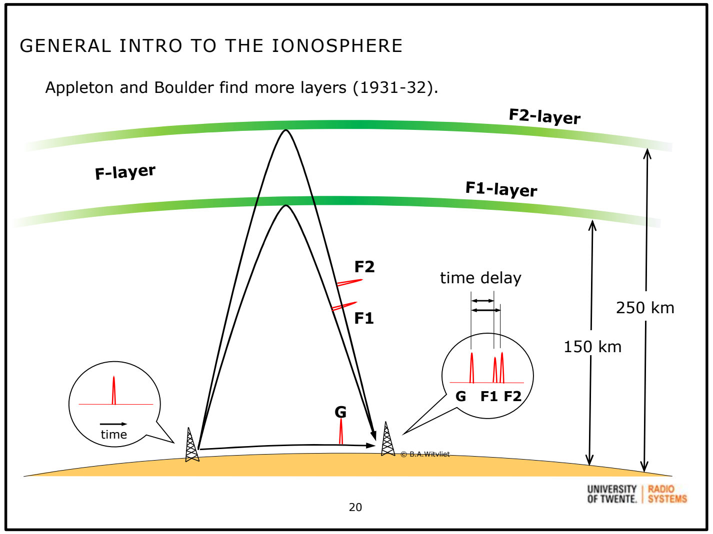
But the very efficient short-wave propagation could not be explained, and this revived the interest in this hypothetical "Heavyside layer".



In 1925, experiments of Gregory Breit and Merle Tuve (USA) prove the existence of this layer. They call it the “electrified layer” or “E-layer”.
They periodically switch on a transmitter and measure the delay of the “hump” in the received amplitude. They conclude that the height of the E-layer is 50 miles or 80 km.
The wavelength they use for their experiments is 71.3 meters, which corresponds to a frequency of 4.2 MHz.

Further reading:

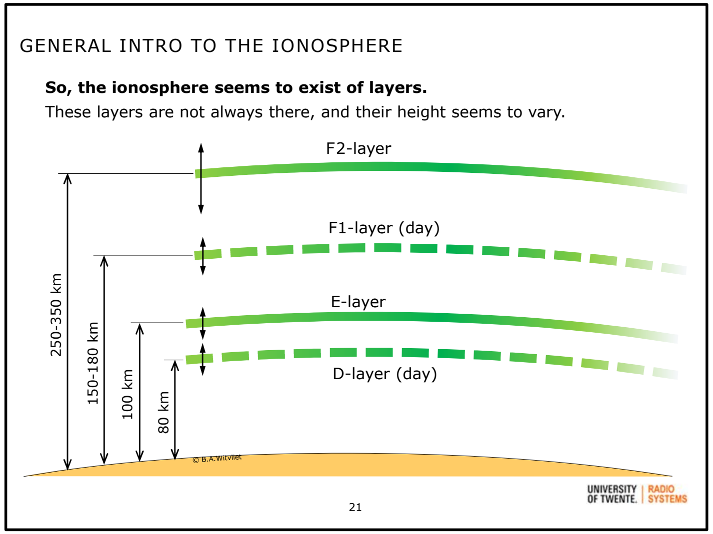
Breit, G., & Tuve, M. A. (1926). A test of the existence of the conducting layer. Physical Review, 28(3), 554.



Between 1931 and 1935 prof. Edward Appleton and Boulder do similar measurements, but with multiple techniques. Using short pulses, they can measure the height of the layers much more accurately.
They discover that next to the E-layer, there is also higher layer, which they call the “F-layer”. This layer splits into two separate layers during daytime, which they call “ F1 and F2-layer”.

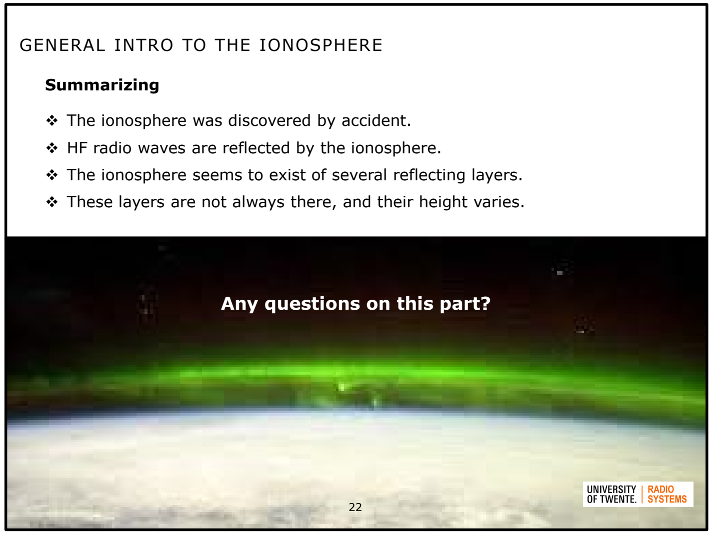
Further reading:

Appleton, E. V., & Builder, G. (1933). The ionosphere as a doubly-refracting medium. Proceedings of the Physical Society, 45(2), 208.



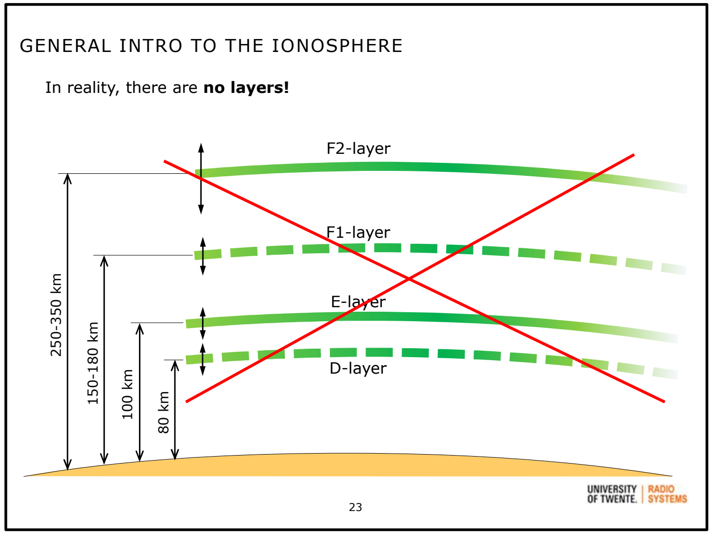
So, the ionosphere seems to consist of layers. Over time, from hour to hour, these layers seem to vary with height. The sounding measurements show that at night, the D-layers disappears completely, and the F1- and F2-layer merge to one F-layer.

The name ‘ionosphere’ was coined by Robert Watson-Watt in 1926 to describe the entire electrified region (the set of reflecting layers, if you will).



Summarizing

- ❖ The ionosphere was discovered by accident.
- ❖ HF radio waves are reflected by the ionosphere.
- ❖ The ionosphere seems to exist of several reflecting layers.
- ❖ These layers are not always there, and their height varies.



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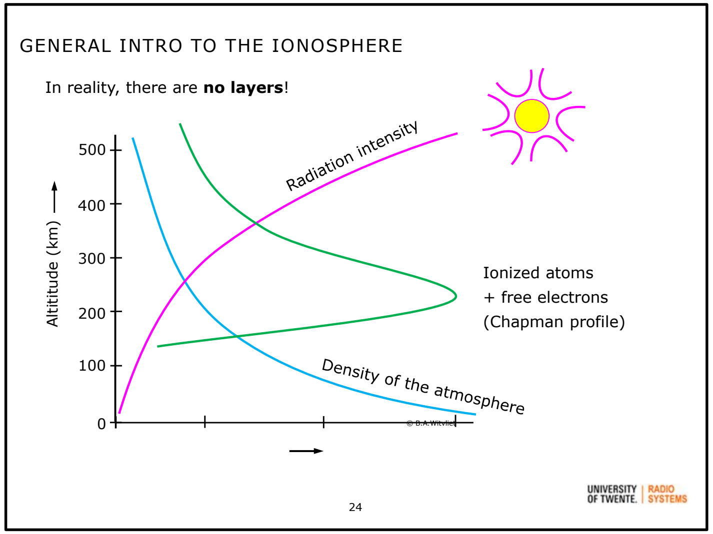
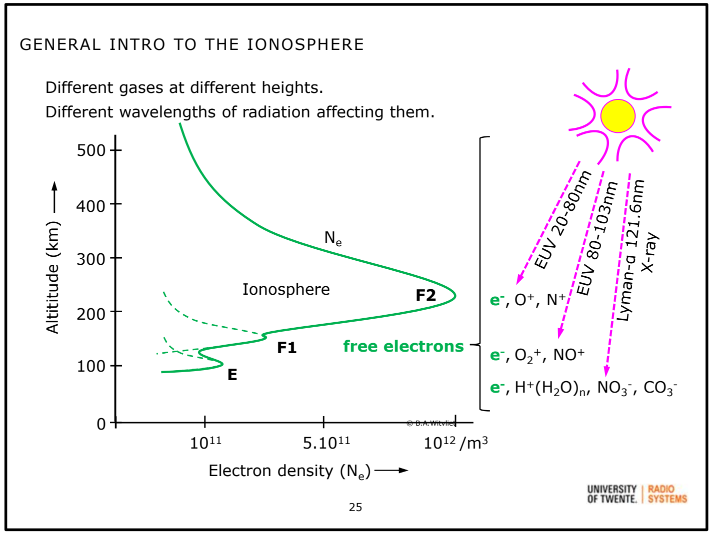


In reality, there are no such layers. The electron density varies smoothly with height.

It is the radiation of the sun that produces these free electrons.

- The density of atoms in the atmosphere decrease with height.
- The radiation of the sun increases with height.
- Therefore the ionization is maximum at a certain height.

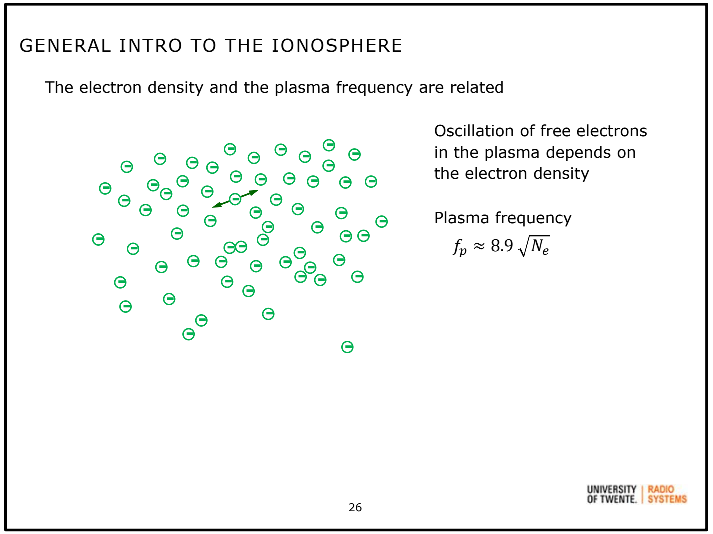
The typical profile of the electron density is described by Sydney Chapman in 1942, and is therefore called the Chapman function.



The atmosphere is not homogeneous, the mix of gases is different at different heights. If there is a different mix of gases, the photo-ionization is also different. And therefore, different wavelengths of solar radiation act on the electron density at different heights. As a result, the electron density profile has a main peak, but also local maxima at lower heights.

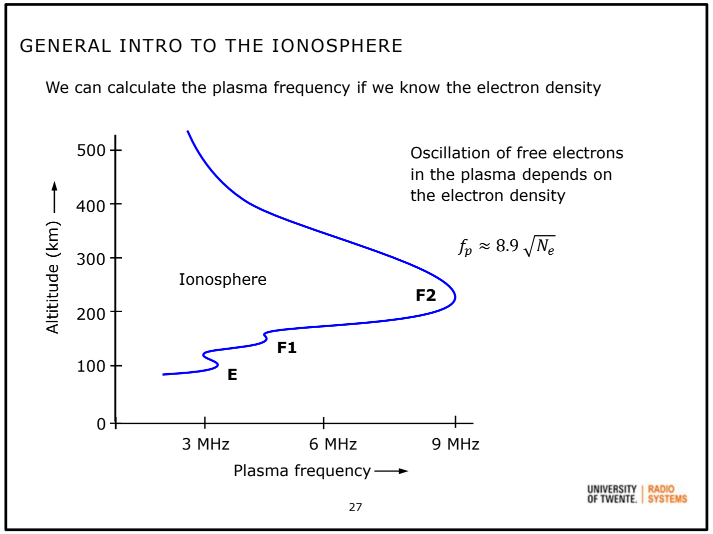
Further reading:

Viggiano, A. A. "Reexamination of ionospheric chemistry: high temperature kinetics, internal energy dependences, unusual isomers, and corrections." in Physical Chemistry Chemical Physics, vol. 8, no. 22, 2006: pp. 2557-2571.



The plasma frequency is the resonant frequency of the electrons in an ionized medium.

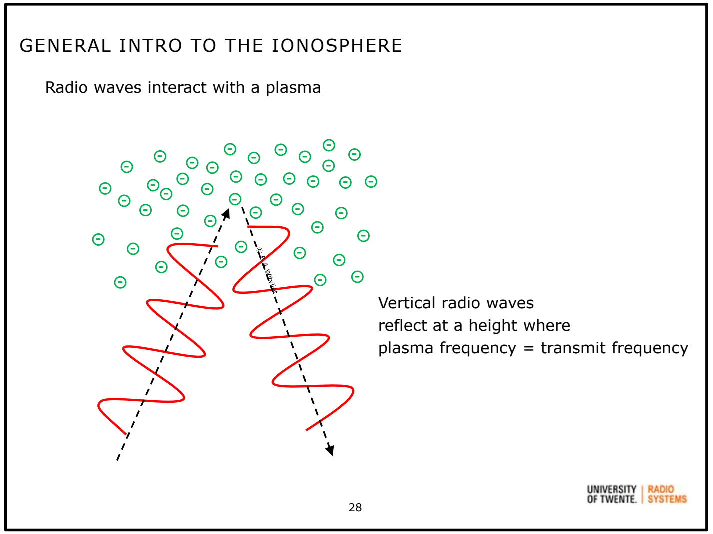
There is a direct relation between the electron density and the plasma frequency, which can be approximated as $f_p \approx 8.9\sqrt{N_e}$.



So if we know this relationship, we can redraw the Chapman electron density profile to become a plasma frequency profile..

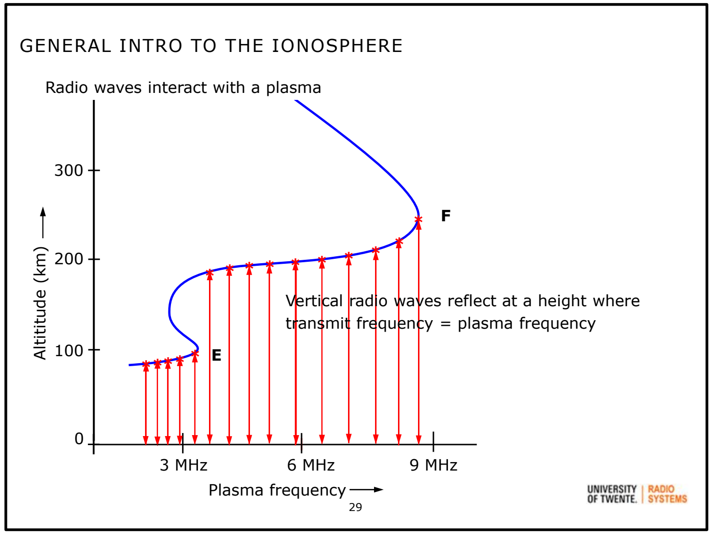
The profile becomes a little ‘fatter’, but the maximum will remain at the same height.

The horizontal axis of the graph now shows plasma frequency in MHz.



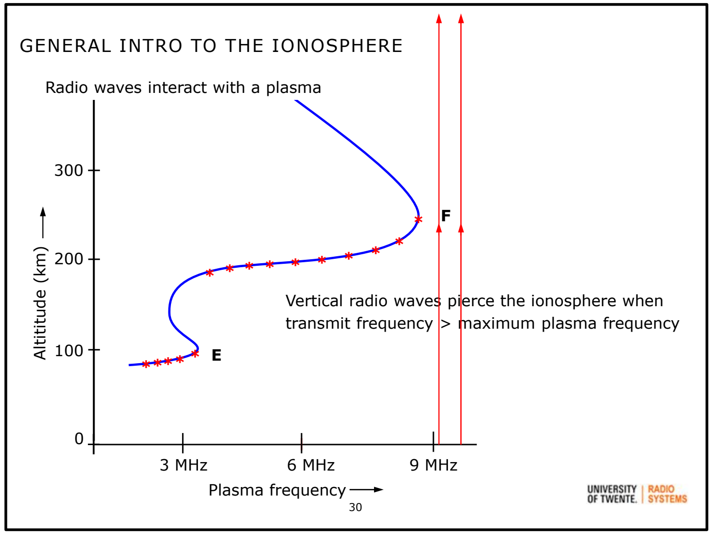
Radio waves interact with a plasma. If we send radio waves vertically upwards, they will reflect at a height where the frequency of the radio wave corresponds with the local plasma frequency.

This is the effect that Appleton and Boulder used for their ionospheric observations. Modern ionosonde observations are based on the same phenomenon.



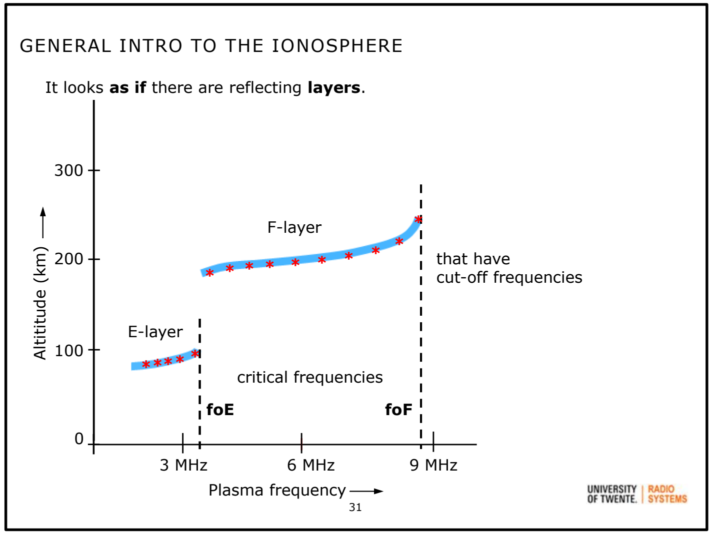
If we send a radio wave of low frequency – let's say 2 MHz - vertically upward, it will be reflected by the ionosphere. If we slowly increase the frequency of the transmitter, we see that the reflection height increases somewhat, but very slowly and gradually.

This continues until at some point, a sudden jump in reflection height is seen. This is happens when we pass a local maximum in the electron density. After that, the reflection height gradually increases, but now a little bit faster.

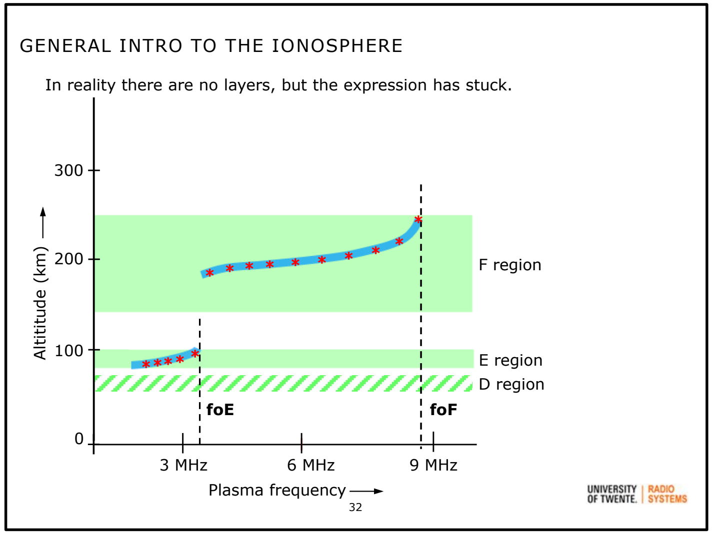


Finally, when the transmit frequency becomes greater than the maximum plasma frequency, the waves pierce the ionosphere and travel into space.

There will no longer be reflected waves, reflected signals are no longer received.



If we draw lines through the reflection points, it looks as if there are two distinct layers.
The reflecting heights of these layers is frequency dependent, and each layer has a distinct cut-off frequency.



In reality there are no layers, but the expression has stuck.
Scientist rather talk about The D-, E- and F-regions.
But as long as we understand each other, the wording we use is not so critical.

GENERAL INTRO TO THE IONOSPHERE

In reality there are no layers, but the expression has stuck.

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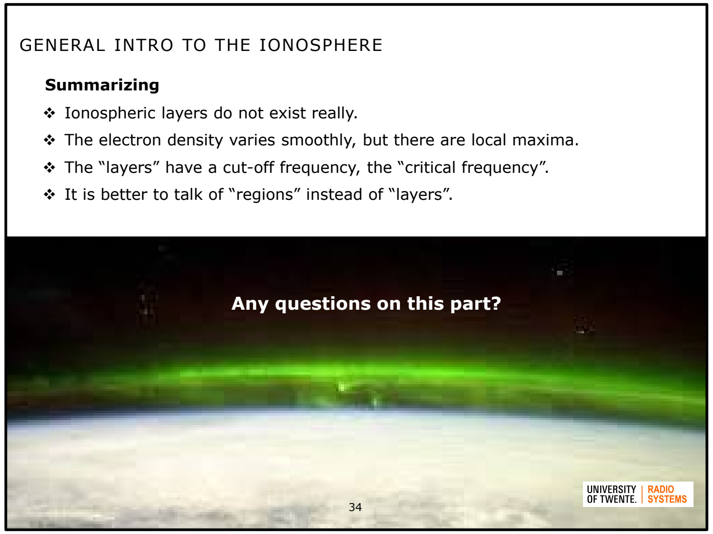
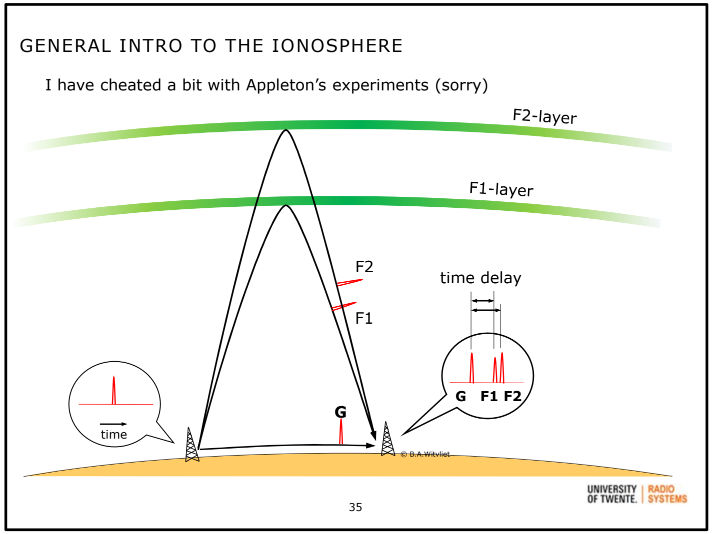
Pictures courtesy of [unknown source]



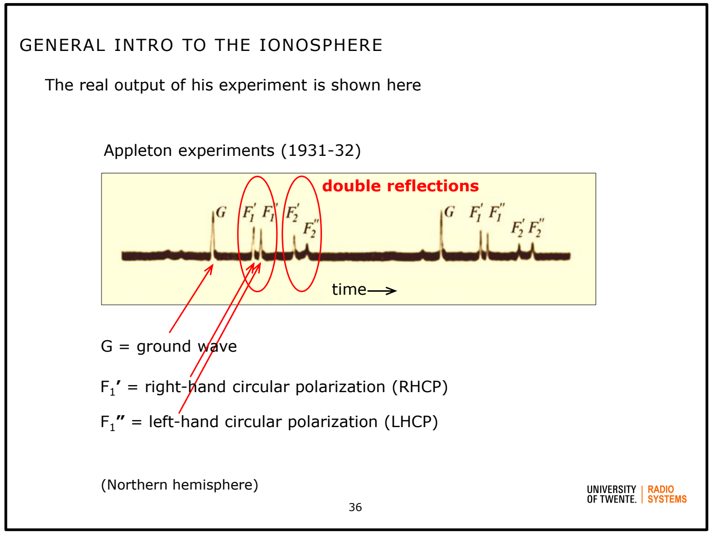
Summarizing

- ❖ Ionospheric layers do not exist really.
- ❖ The electron density varies smoothly, but there are local maxima.
- ❖ The "layers" have a cut-off frequency, the "critical frequency".
- ❖ It is better to talk of "regions" instead of "layers".

Aurora seen from space. Pictures courtesy of NASA.



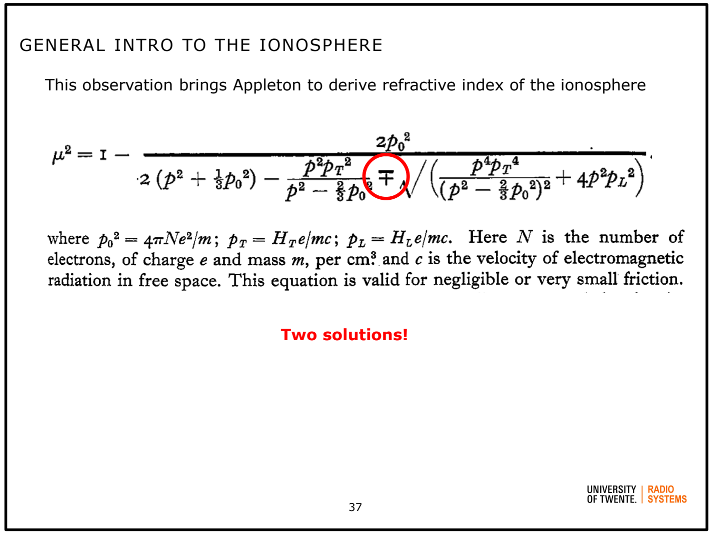
I have cheated a bit when I presented the experiments of Appleton and Boulder. For the sake of simplicity, I have only shown a single reflection from each layer.



This is the true output of his experiment. It photo of the oscilloscope he used.
I took this from a paper he published in 1932 and did a lot of filtering to make it presentable again ☺.

In the photograph you see the groundwave pulse (G), but the reflections from the F1- and F2-layer are double!

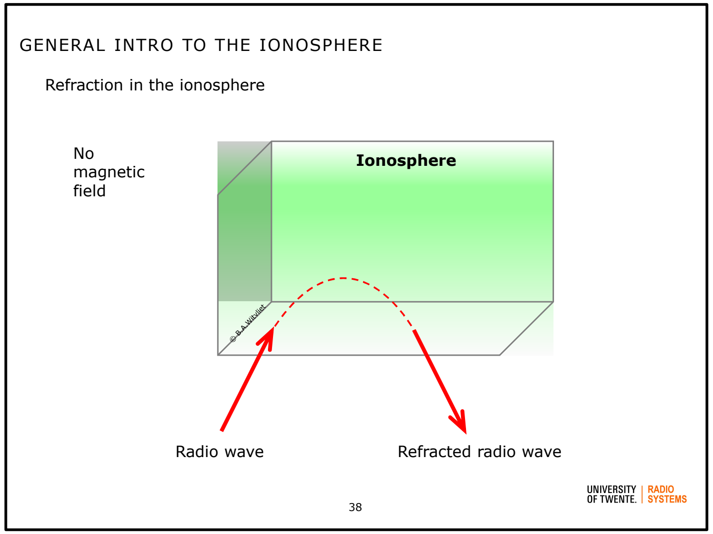
Original picture is from Appleton, E. V., and G. Builder (1933), "The Ionosphere as a Doubly-Refracting Medium,“ Proc. Phys. Soc., 45, (2), pp. 208-220.
Postprocessed picture can be found in Witvliet, Ben A., et al. Measuring the isolation of the circularly polarized characteristic waves in NVIS propagation [Measurements Corner]. IEEE antennas and propagation magazine, 2015, 57.3: 120-145 (copyright: IEEE).



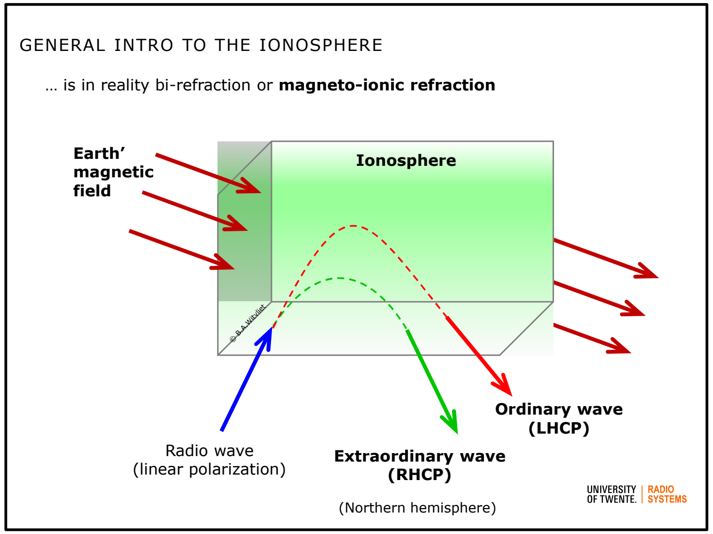
To explain these observations, Appleton derived a formula that describes the refraction in a plasma (the ionosphere) in the presence of a magnetic field (of the Earth).

The formula has a ± sign in it, meaning that there are two possible outcomes!
One of them is the “ordinary wave”, the other one is the “extraordinary wave”.

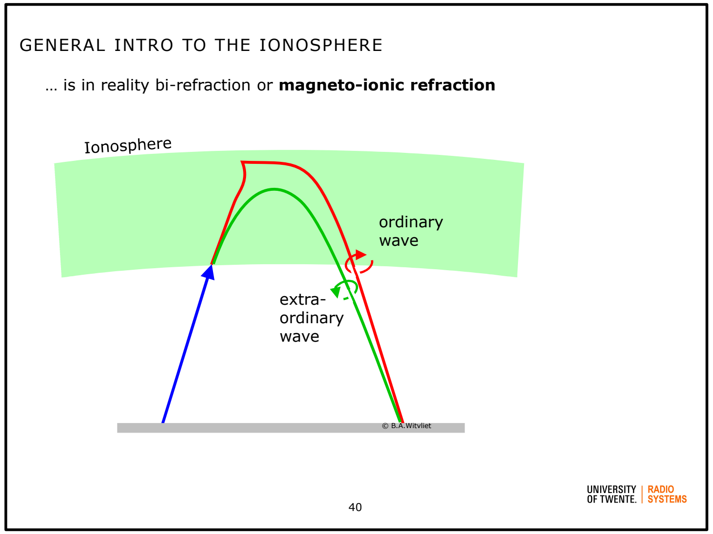
Text from Appleton, E. V., and G. Builder (1933), "The Ionosphere as a Doubly-Refracting Medium,“ Proc. Phys. Soc., 45, (2), pp. 208-220.



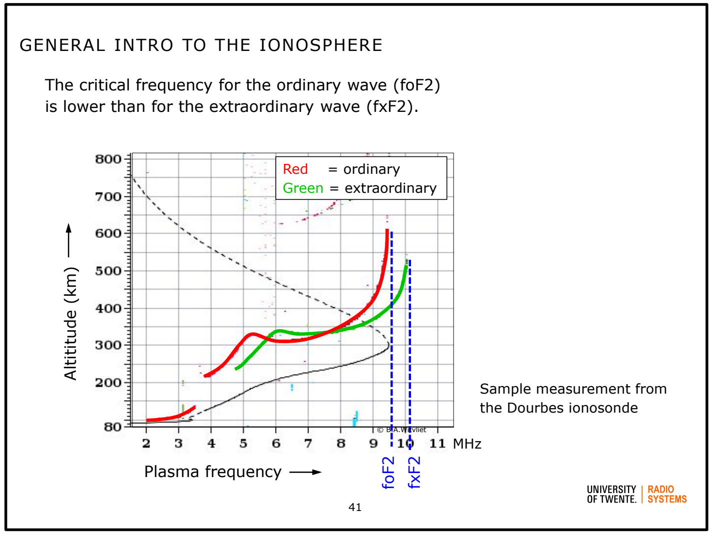
From these formulas we can also see that, when there is no magnetic field, there will be a single refractive index. Radio waves will be refracted in a plasma.



However, when there is a magnetic field present, only circular polarized waves can propagate in the ionosphere. Therefore, the linear polarized wave splits into two complementary circular polarized waves, which then continues traveling through the ionosphere.

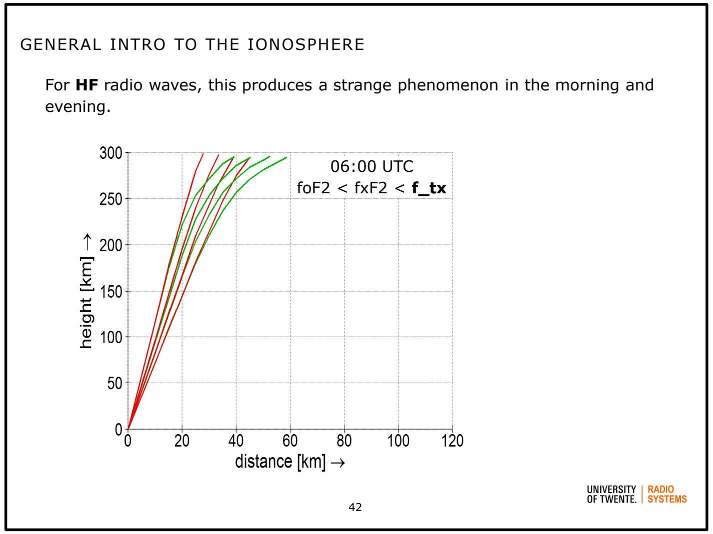


As the refractivity is different for the ordinary (O) wave and the extraordinary (X) wave, they travel different paths.
In the Northern hemisphere, the downward ordinary wave is Left-Hand Circular Polarization (LHCP) and the downward extraordinary wave is Right-Hand Circular Polarization (RHCP).



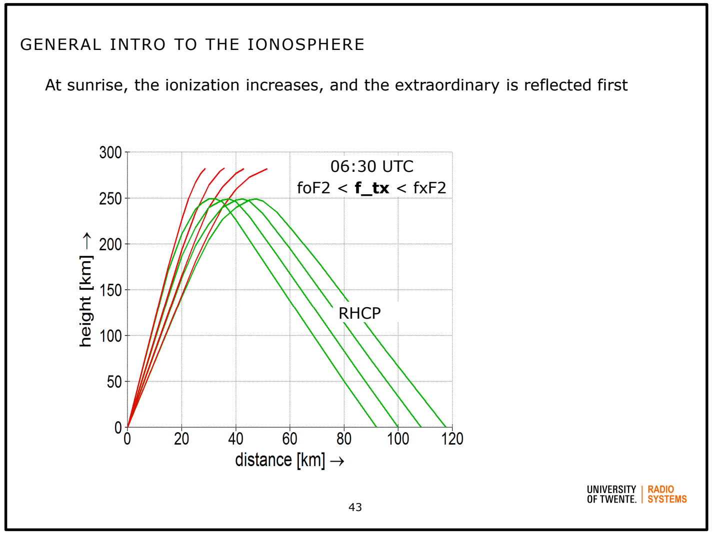
From this formula also follows that there are two critical frequencies, one for the ordinary and one for the extraordinary wave. This can be seen in the measurement of an ionosonde, a radar that sends waves of increasing frequency upward to the ionosphere, similar to Appleton's experiments. The picture shown here is from the Dourbes ionosonde in Belgium. The green and red curves are similar, but their critical frequencies are slightly different. It looks as if – again only as if – there are two different layers that we observe.

For further study:
Graphic representations of Dourbes ionosonde measurements can be found on https://digisonde.oma.be/



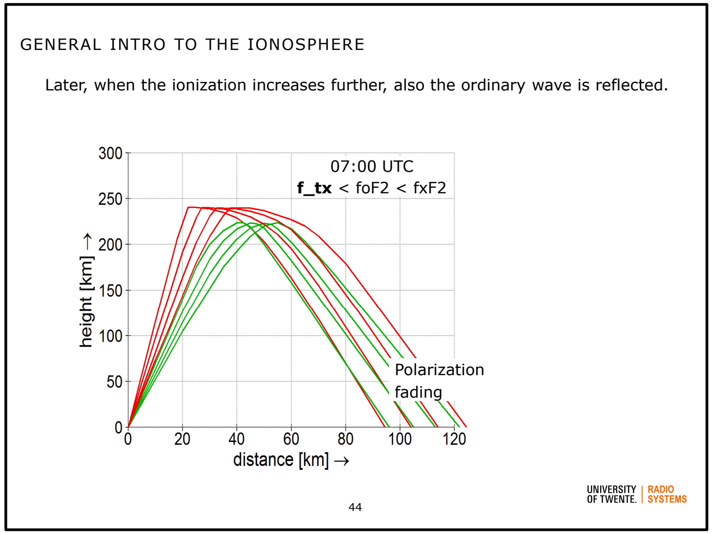
As a result, something strange happens when we observe HF (3-30 MHz) radio signals. In the morning, when the ionization is low, radio waves with a frequency of, for example, 7 MHz pierce the ionosphere and disappear in space…
These graphs are made with PropLab Pro, an ionospheric raytracing program.

Picture taken from Witvliet, Ben A., et al. Measuring the isolation of the circularly polarized characteristic waves in NVIS propagation [Measurements Corner]. IEEE antennas and propagation magazine, 2015, 57.3: 120-145 (copyright IEEE).



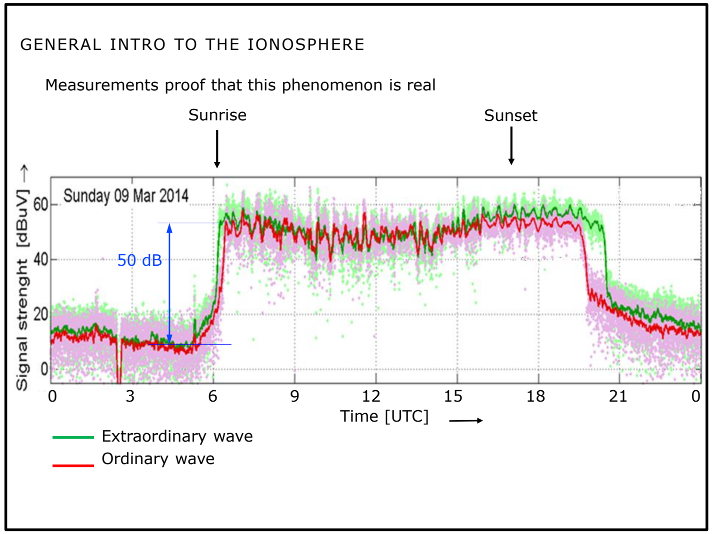
When the sun comes up and start to irradiate the ionosphere, the electron density goes up quickly, until at some point the peak plasma frequency is high enough, and the radio waves are reflected back to Earth.
As the critical frequency for the extraordinary wave (fxF2) is higher, extraordinary waves are the first to be reflected. The ordinary waves still pierce the ionosphere.
As a consequence, only right-hand circularly polarized (RHCP) signals will arrived back on Earth (Northern hemisphere).

Picture taken from Witvliet, Ben A., et al. Measuring the isolation of the circularly polarized characteristic waves in NVIS propagation [Measurements Corner]. IEEE antennas and propagation magazine, 2015, 57.3: 120-145 (copyright IEEE).



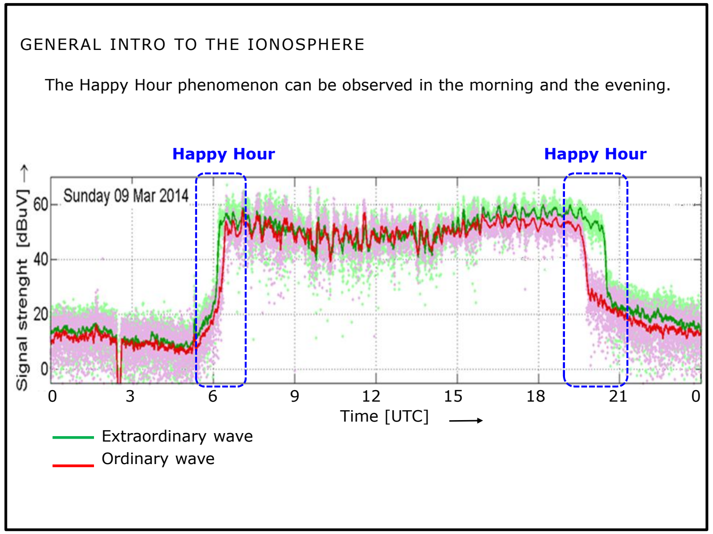
When the sun rises further, the ionization increases further, and now also the critical frequency for the ordinary waves is reached. Both waves are now refracted back to Earth, but clearly their path is very different.
As the waves interfere, the resulting polarization varies rapidly. We call this "polarization fading".

Experimental proof of this "Happy Hour" can be found in Witvliet, Ben A., et al. Measuring the isolation of the circularly polarized characteristic waves in NVIS propagation [Measurements Corner]. IEEE Antennas and Propagation Magazine, 2015, 57.3: 120-145 (copyright IEEE).



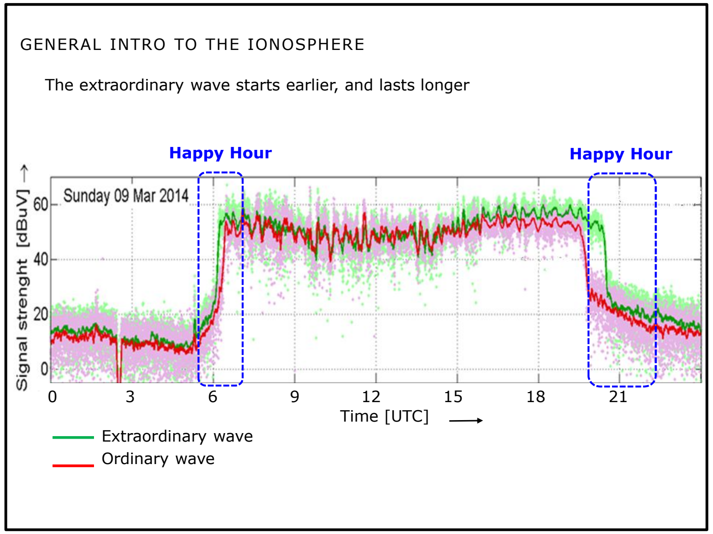
These graphs show the signal strength from an experiment over a 110-km HF radio path at 7 MHz. Measurements are done with RHCP (green) and LHCP (red) antennas. In the morning, at sunrise, the ionization of the ionosphere rises sharply, and first the extraordinary wave and then the ordinary wave are reflected. In the evening, after sunset, the ionization slowly diminishes. This process is much slower due to recombination and diffusion.

Measurements that were also reported in Witvliet, Ben A., et al. Measuring the isolation of the circularly polarized characteristic waves in NVIS propagation [Measurements Corner]. IEEE Antennas and Propagation Magazine, 2015, 57.3: 120-145.



In the morning there is an half-hour interval in which only RHCP is received, the "Happy Hour". In the evening the happy Hour has a longer duration, varying from 1 to 2 hours. The duration of the propagation of the extraordinary wave is much longer than that of the extraordinary wave.

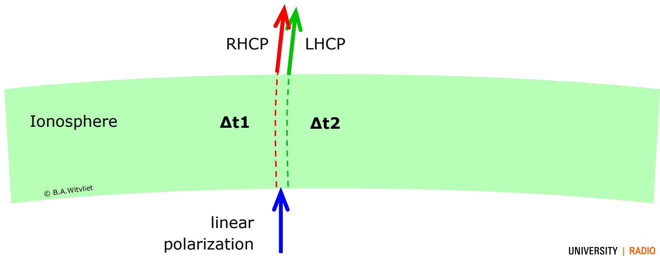
Picture taken from Witvliet, Ben A., et al. Measuring the isolation of the circularly polarized characteristic waves in NVIS propagation [Measurements Corner]. IEEE antennas and propagation magazine, 2015, 57.3: 120-145 (copyright IEEE).



This phenomenon occurs every day.

Picture taken from Witvliet, Ben A., et al. Measuring the isolation of the circularly polarized characteristic waves in NVIS propagation [Measurements Corner]. IEEE antennas and propagation magazine, 2015, 57.3: 120-145 (copyright IEEE).

At **higher frequencies** both waves pierce the ionosphere,
but the **delay** of the ordinary and extraordinary wave **is not the same**.



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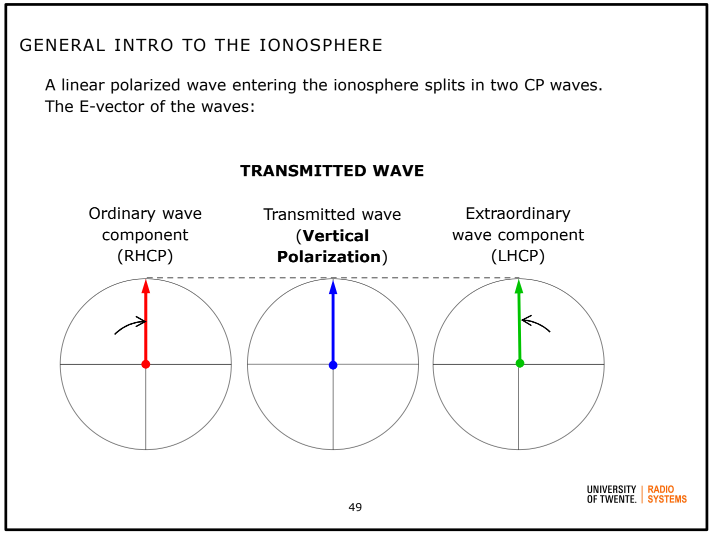
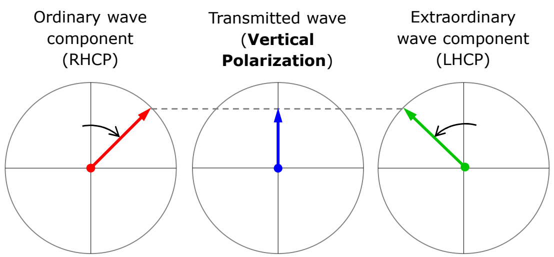


A linear polarized wave entering the ionosphere splits in two CP waves, that rotate in the opposite sense.

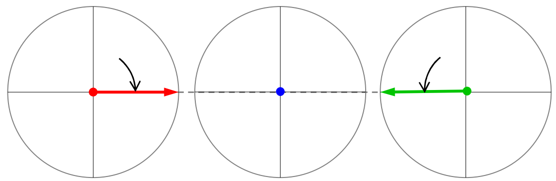
A linear polarized wave entering the ionosphere splits in two CP waves.
The E-vector of the waves:

TRANSMITTED WAVE



A linear polarized wave entering the ionosphere splits in two CP waves.
The E-vector of the waves:

TRANSMITTED WAVE



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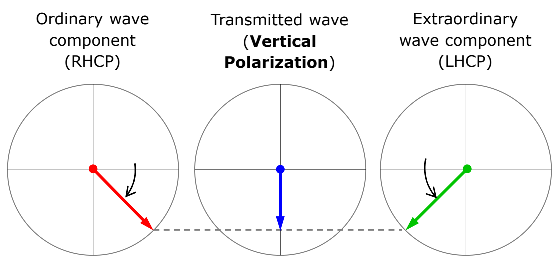
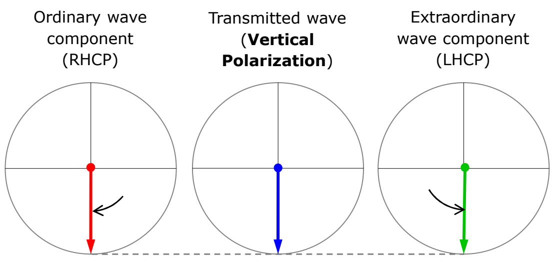
A linear polarized wave entering the ionosphere splits in two CP waves.
The E-vector of the waves:

TRANSMITTED WAVE



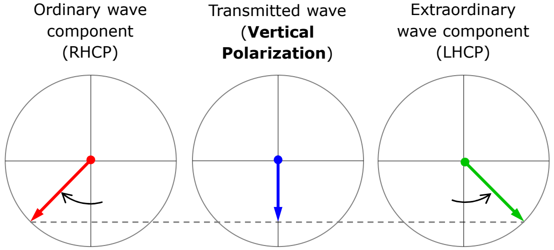
A linear polarized wave entering the ionosphere splits in two CP waves.
The E-vector of the waves:

TRANSMITTED WAVE



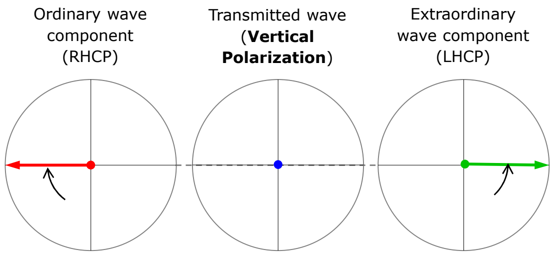
A linear polarized wave entering the ionosphere splits in two CP waves.
The E-vector of the waves:

TRANSMITTED WAVE



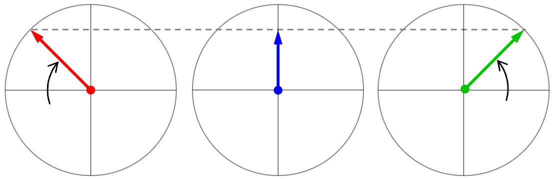
A linear polarized wave entering the ionosphere splits in two CP waves.
The E-vector of the waves:

TRANSMITTED WAVE



A linear polarized wave entering the ionosphere splits in two CP waves.
The E-vector of the waves:

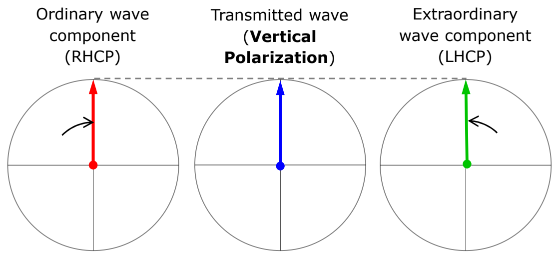
TRANSMITTED WAVE



GENERAL INTRO TO THE IONOSPHERE

A linear polarized wave entering the ionosphere splits in two CP waves.
The E-vector of the waves:

TRANSMITTED WAVE



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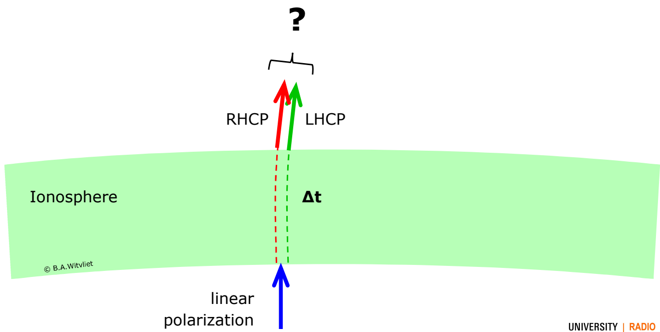
So now let's look what happens if one of the waves is delayed



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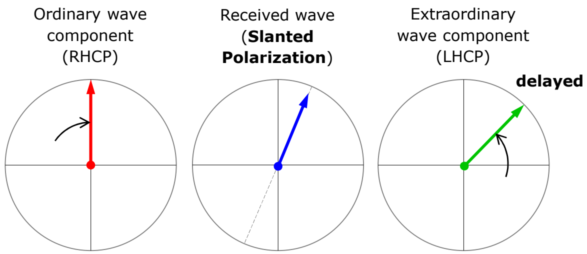
GENERAL INTRO TO THE IONOSPHERE

A linear polarized wave entering the ionosphere splits in two CP waves.
The E-vector of the waves:

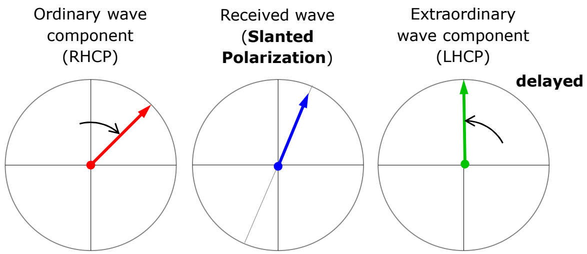
RECEIVED WAVE



When they exit the ionosphere, their delay is not longer the same.
When we now add those two CP waves, we will get a linear polarized wave again.
But the resulting polarization angle has changed.

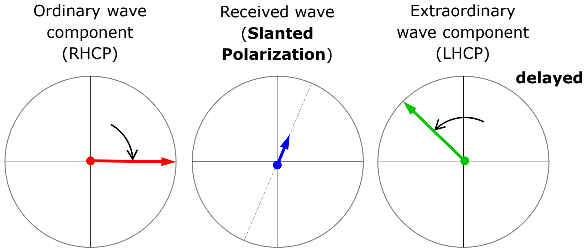
A linear polarized wave entering the ionosphere splits in two CP waves.
The E-vector of the waves:

RECEIVED WAVE



A linear polarized wave entering the ionosphere splits in two CP waves.
The E-vector of the waves:

RECEIVED WAVE

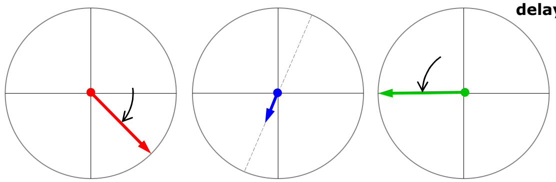


A linear polarized wave entering the ionosphere splits in two CP waves.
The E-vector of the waves:

RECEIVED WAVE

Ordinary wave component (RHCP)	Received wave (**Slanted Polarization**)	Extraordinary wave component (LHCP)

delayed



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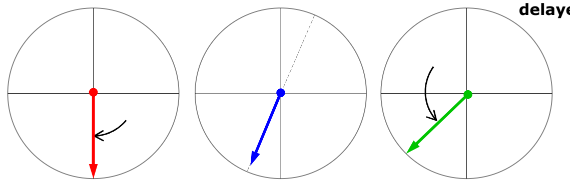
GENERAL INTRO TO THE IONOSPHERE

A linear polarized wave entering the ionosphere splits in two CP waves.
The E-vector of the waves:

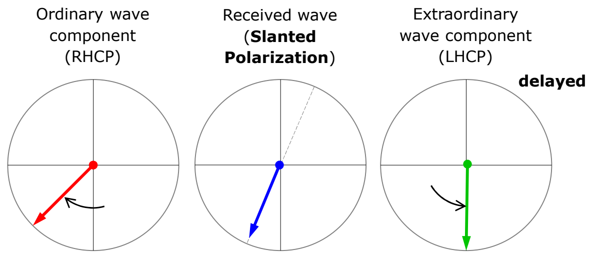
RECEIVED WAVE

Ordinary wave component (RHCP)	Received wave (**Slanted Polarization**)	Extraordinary wave component (LHCP) **delayed**



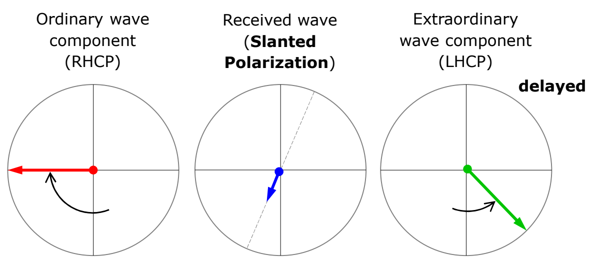
A linear polarized wave entering the ionosphere splits in two CP waves.
The E-vector of the waves:

RECEIVED WAVE



A linear polarized wave entering the ionosphere splits in two CP waves.
The E-vector of the waves:

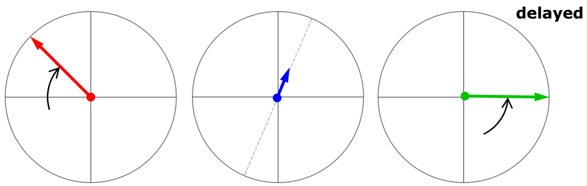
RECEIVED WAVE



A linear polarized wave entering the ionosphere splits in two CP waves.
The E-vector of the waves:

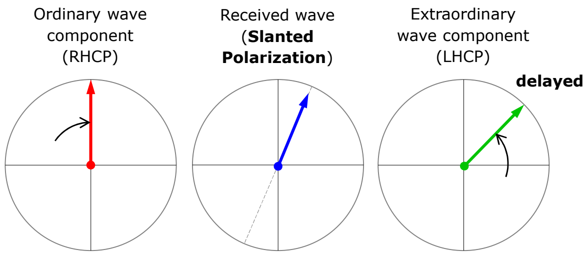
RECEIVED WAVE

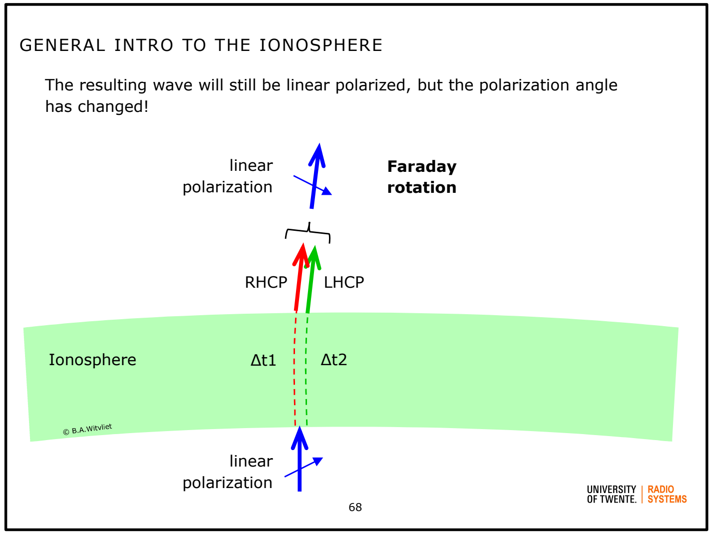
Ordinary wave component (RHCP)	Received wave (**Slanted Polarization**)	Extraordinary wave component (LHCP)



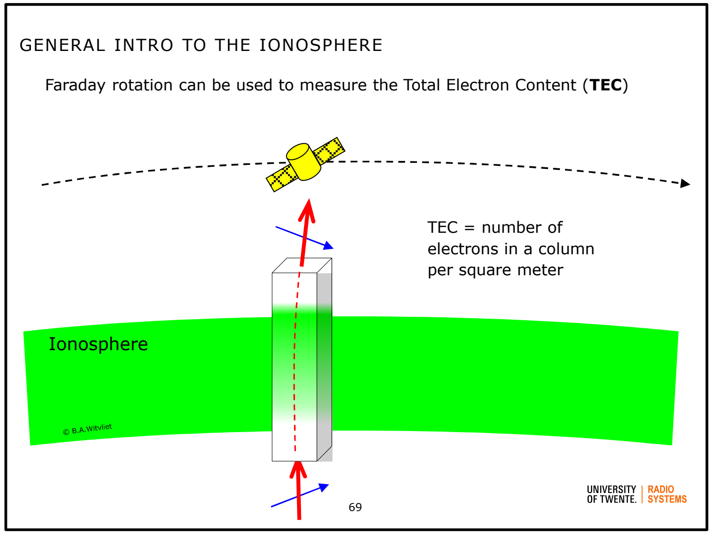
A linear polarized wave entering the ionosphere splits in two CP waves.
The E-vector of the waves:

RECEIVED WAVE



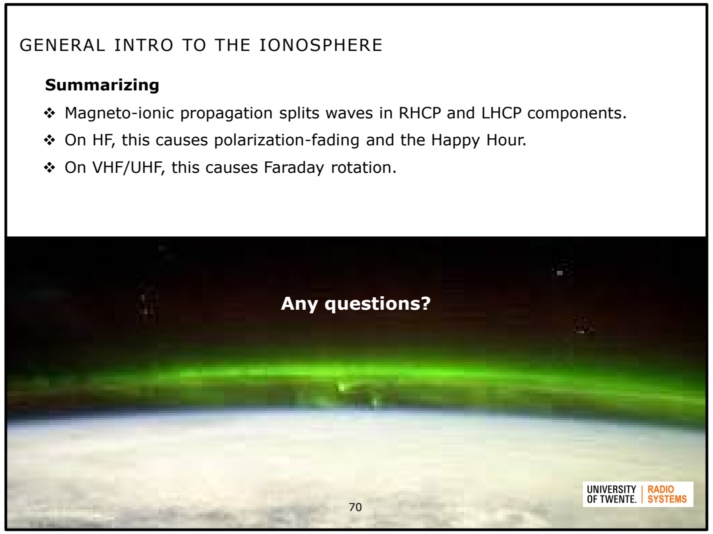


So, when the waves pierce the ionosphere at higher frequencies, the ionosphere causes a polarization change.
Linear polarized waves will stay linear polarized, but their polarization angle has changed.
This is called "Faraday rotation".



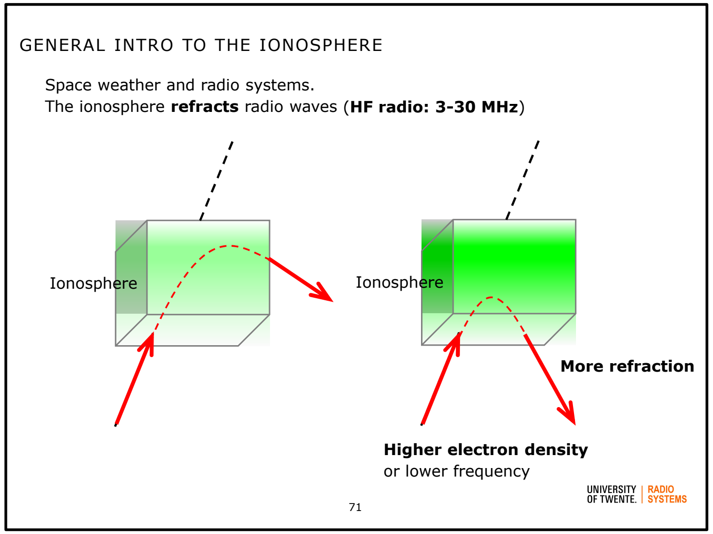
The Faraday rotation can be used to measure the total number of electrons that the waves encountered on their path. Generally, this is expressed as the total number of electrons in a straight column along the wave path. This number is called the Total Electron Content (TEC) . One TEC-unit (TECU) is 106 electrons/m2.

If the wave passes vertically through the ionosphere, that column is vertical, and we call the measured number of electrons Vertical TEC or VTEC. If the waves pass through the ionosphere along a slanted path, we call it Slanted TEC or STEC. Measured TEC does not give you information on the local electron density in one of the ionospheric layers, or on the peak electron density.



Summarizing

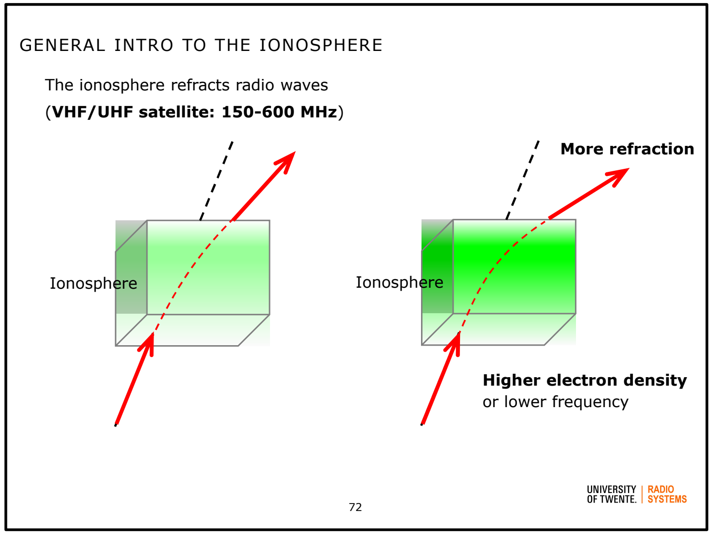
❖ Magneto-ionic propagation splits waves in RHCP and LHCP components.
❖ On HF, this causes polarization-fading.
❖ On VHF/UHF, this causes Faraday rotation.



Now let’s have a look what the ionosphere does to our radio applications.

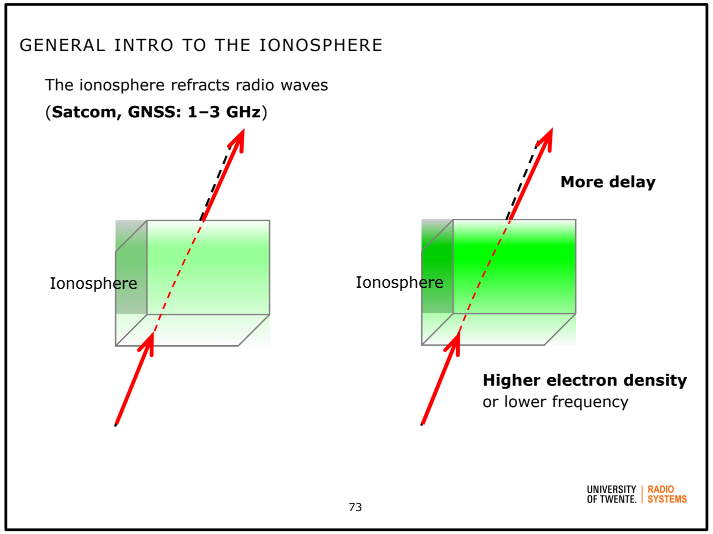
Firstly, we look at HF radio

We have seen that vertical waves at frequencies below the maximum plasma frequency are reflected. But also waves that enter the ionosphere at an angle will be bent back to earth, up to approximately up to approximately 3x the maximum plasma frequency. Typically, these frequencies are below 30 MHz. On rare occasions frequencies up to 150 MHz are reflected.

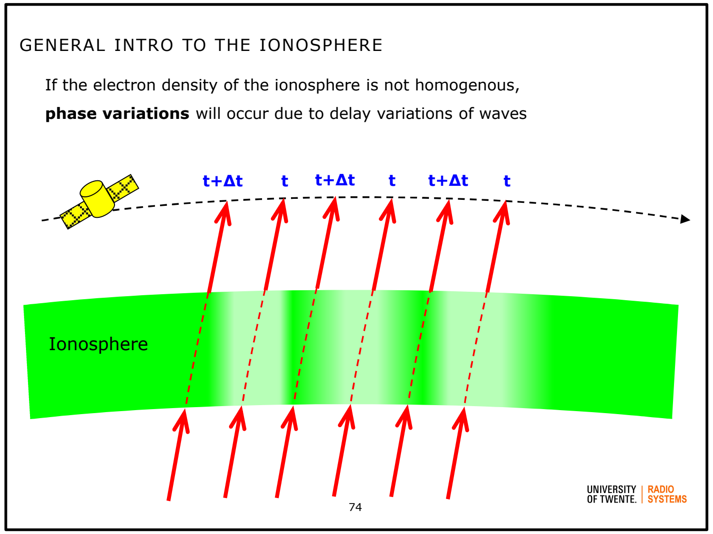


If we look at VHF/UHF satellite signals,
at frequencies between 150 and 600 MHz, the radio waves will pierce the ionosphere with little attenuation. But the waves will be refracted, and the signals will deviate from a straight line path. The satellites will be received on the ground slightly before they appear above the horizon.

The refraction will depend on the (local) electron density. A higher electron density will result in more refraction. Also – for the same electron density – higher frequencies will be less affected.



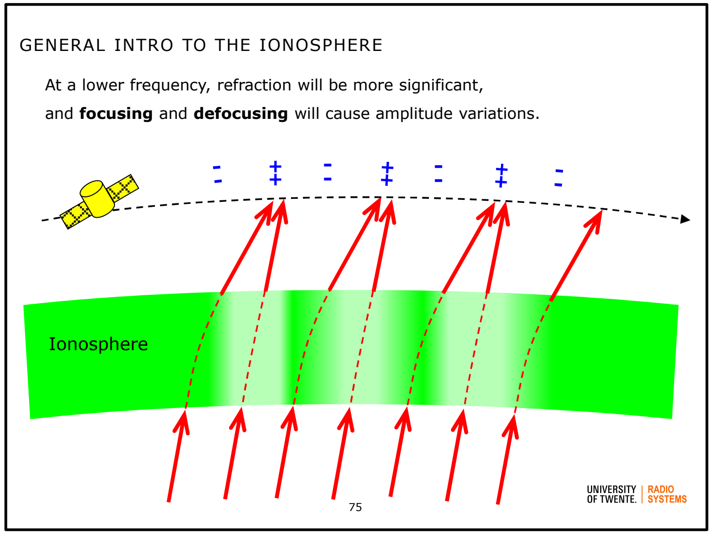
SHF satcom and GNSS
At still higher frequencies, the radio waves do not longer deviate much from a straight line, just a little bit. However, there is still a delay, which depends on (again) the electron density and the frequency.
The examples are all shown with signals going upward, but the explanations also hold for downward signals.



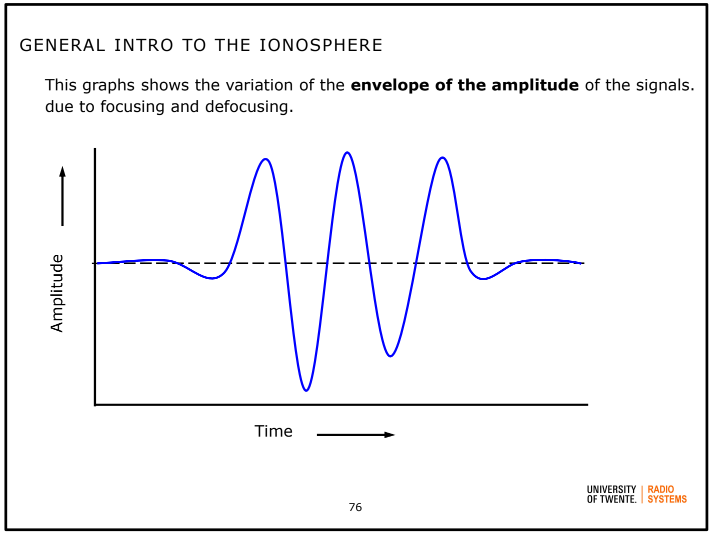
So far, we assumed a stable and predictable ionosphere. That is not always the case. At high frequencies, were there is only a little refraction, the the delay imposed on radio waves may still be important. When – either due to the movement of the satellite or due to traveling ionospheric disturbances - the radio signals travel through dense and underdens sections of the ionosphere, a variation in path delay will occur. As a result, a satellite moving about or through an inhomogeneous ionosphere will receive the signal, but with rapid phase variations superimposed on it.

Depending on the severity of these phase variations, the receiver may loss signal lock. The intensity of the phase variation is generally expressed as the Phase Scintillation Index ($\sigma\varphi$).

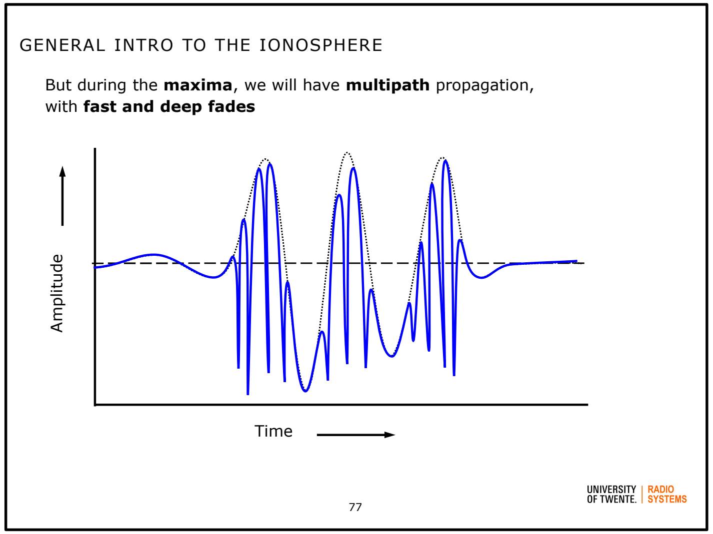
The examples are all shown with signals going upward, but the explanations also hold for downward signals. The upward case is easier to draw and explain without resorting to more complex animations.



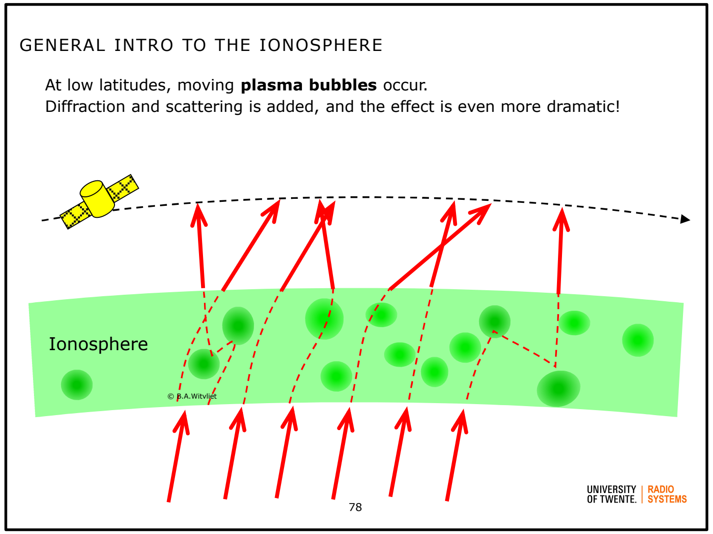
At slightly lower frequencies, or when the electron density variations are large, the effect of ionospheric refraction is more prominent. As a result focusing and defocusing (lensing) will occur, which will cause the amplitude of the satellite signals to go through maxima and minima. For simplicity, this example shows transmissions from earth to satellite, but the path is reciprocal.



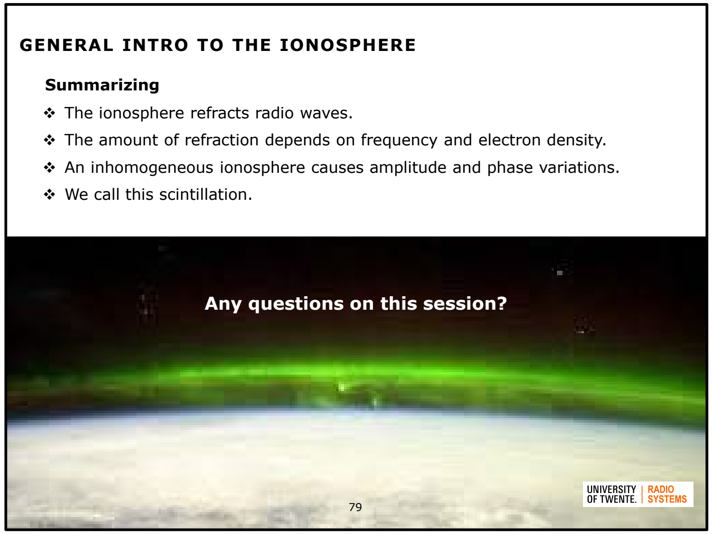
From the previous case, we could draw the power density variation due to the focusing and defocusing effect. However, this is not the full story…



In the focusing, multiple waves come together and interfere. Depending on the difference in path length, this will be additive or destructive interference. During destructive interference, deep fades (of more than 30 dB) will occur. And with changing path lengths, additive and destructive phase will follow each other in sequence. The phase of the resulting signal will vary fast during these deep fades. This results in a rapid amplitude variation as shown above. The intensity of the amplitude variation is generally expressed as the Amplitude Scintillation Index (S4).



In the equatorial region, rising plasma bubbles will cause a much more complex system still. As they are moving fast, they will also add Doppler shift to the signal.



<u>Summarizing</u>
❖ The ionosphere refracts radio waves.
❖ The amount of refraction depends on frequency and electron density.
❖ An inhomogeneous ionosphere causes amplitude and phase variations.
❖ We call this scintillation.

Aurora seen from space. Picture courtesy of NASA.