



Radio communication

■ Lecturer and credits

Your lecturer:
Dries Van Baelen

Belgian MoD, Directorate General of Material Resources

With major contributions and inspiration from:

- [1] Major Willem-Pieter van der Laan *Royal Netherlands Airforce, Royal Netherlands Meteorological Institute*
- [2] Australian Space Weather Forecasting Centre [SWS - Other Topics - Introduction to HF Radio Propagation](#)
- [3] The fantastic STCE who taught me what's behind all of this



■ Outline

- Radio communication from viewpoint of users & managers
- Discussion of frequency bands
 - Propagation mechanisms
 - Behaviour
 - Applications

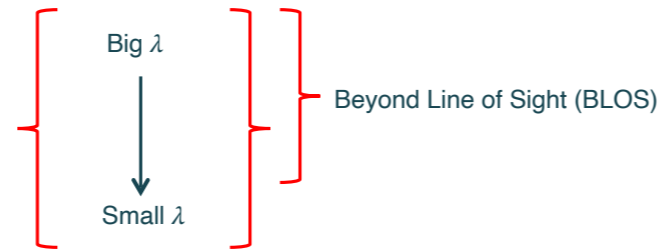
■ Propagation types

■ Propagation types

- Waves propagate due to different physical mechanisms
 - Of course all resulting from Maxwell's equations
- Not all mechanisms are predominant / relevant in every frequency band

■ Propagation types

- Waveguide
- Ground wave
- Skywave
- Line-of-Sight (LOS)



Other methods of electromagnetic propagation exist, but they are not discussed in this course:
Think of guided waves through a coax cable and over unshielded wires

Radio bands

Band Nr (ITU)	Abbreviation	Frequency Range	Wavelength Range
1 – 3	ELF, SLF, ULF	<3 kHz	>100 km
4	VLF	3 to 30 kHz	10 to 100 km
5	LF	30 to 300 kHz	1 to 10 km
6	MF	300 to 3000 kHz	100 to 1000 m
7	HF	3 to 30 MHz	10 to 100 m
8	VHF	30 to 300 MHz	1 to 10 m
9	UHF	300 to 3000 MHz	10 to 100 cm
10	SHF	3 to 30 GHz	1 to 10 cm
11	EHF	30 to 300 GHz	1 to 10 mm

$$c = \lambda \cdot f$$



navigation, time syncing...
 Many applications: Radar, SATCOM, GPS, classic WiFi & Bluetooth.
 used in the ionosphere to propagate over the horizon.
 HF terminal (US initiative together with Canada, NL en UK)

Note that the size of an antenna scales with its wavelength of operation. $\lambda/4$ is a typical size

Remember the relation between wavelength and frequency and find the speed of light: $3 \cdot 10^8$ m/s. This speed fixes the radio bands: frequencies are tenfolds of 3Hz, wavelengths of 10m. Shown here are the bands defined by the ITU: the International Telecommunication Union. They have an ITU-number and an abbreviation. These abbreviations are widely used, however there are other definitions. They depend on the community and application. E.g. the IEEE and NATO use other names. This can be very confusing as some names are used for different bands. Therefore we stick to the ITU-bands. If you ever talk with others about radio bands, please make sure you know about which frequencies (or wavelengths) you talk. The frequencies dictate the physics.

Follow the hyperlinks for more information on the different band. For now, let's have a look on four of them.

@VLF: Navy (submarines, UK broadcast), Air Force (time syncing on UHF radios, needed for frequency hopping, GE broadcast @ 77,5kHz).

@HF: widely used by military and amateurs. Uses the ionosphere as a mirror for communication over the horizon.

@UHF: has a lot of applications. Radar, SATCOM, C2000 & GPS.

@EHF: SMART-T = AEHF terminal, US initiative together with Canada, NL en UK.

Q: looking at the different bands and the pictures of the associated antennas, what do we see? A: antennas scale with wavelength. A quarter lambda or half lambda is widely used as the size of an antenna.

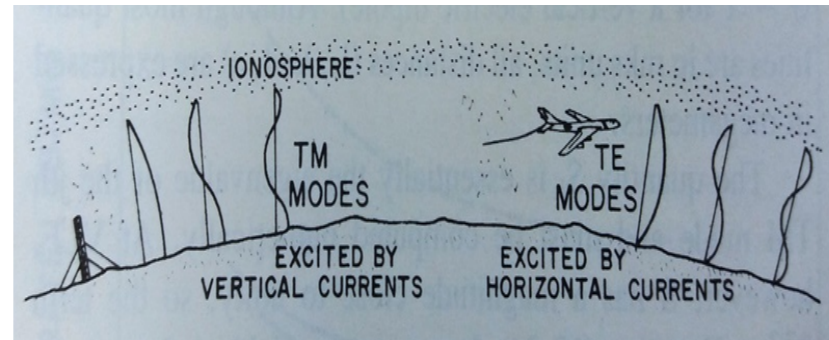
Frequency band

ELF-VLF

■ Propagation at ELF & VLF

- Waveguide propagation
- Surface waves

■ ELF/VLF: Waveguide propagation ($f < 30$ kHz)



The denser the D layer ionization, the better the propagation

→ Impact of SWx!

For ELF: only vertically polarized TEM mode:
Distance D-layer \leftrightarrow Earth is $\ll \lambda/2$



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Waveguides restrict waves in one direction thereby reducing loss. Think of an optic fiber that guides light in one direction. The principle is based on reflection at the walls of the guide. These prevent the wave to expand spherically. To reflect the walls should be conductive. As a rule of thumb, the width of a waveguide needs to be of the same order of magnitude as the wavelength of the guided wave.

Both Earth and the ionosphere are conductive. The height of the D-layer varies between 70 km (day) and 90 km (night). This means that waves in the ELF/VLF-bands are guided. Multiples of this length have to fit for optimal transmission. A denser D-layer better reflects the radiowaves, while a lower or higher D-layer changes the optimal frequencies. For VLF, the so-called mode (TE or TM) depends on the orientation of the antenna. For the lower frequencies where the distance between the D-layer and the Earth is much less than one wavelength, only the vertically polarized TEM mode can propagate.

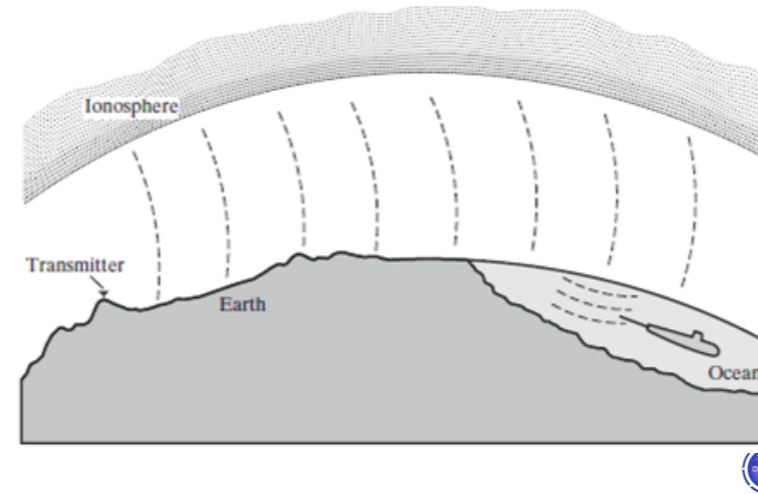
ELF/VLF are typically used for communications with submarines as the waves penetrate seawater to a depth of tens of meters. Although the used transmit antennas are gigantic, they are still electrically very short since on these frequencies, their size is significantly less than $\lambda/4$. Therefore, they are extremely inefficient, causing the few transmit stations that exist on these bands to require huge transmit powers (up to megawatts) for an effective radiated output of a few watts. Because of the very low attenuation of these frequencies however, this suffices for worldwide coverage. Receive antennas are easier, since a simple ferrite loop suffices already.

<https://en.wikipedia.org/wiki/Waveguide>

https://en.wikipedia.org/wiki/Earth%E2%80%93ionosphere_waveguide

<https://www.chegg.com/homework-help/vlf-propagation-earth-ionosphere-waveguide-height-terrestria-chapter-10-problem-4p-solution-9780132662741-exc>

■ ELF/VLF: Waveguide propagation ($f < 30$ kHz)



Freqs permeate some tens of meters through seawater

- Ideal for communication to submarines
- Low frequency, low bandwidth, low data rate



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■ Propagation mechanism matrix

Wavelength Range	Abbreviation	Waveguide	Ground wave	Skywave	Line of Sight
>100 km	ELF				
10 to 100 km	VLF				
1 to 10 km	LF				
100 to 1000 m	MF				
10 to 100 m	HF				
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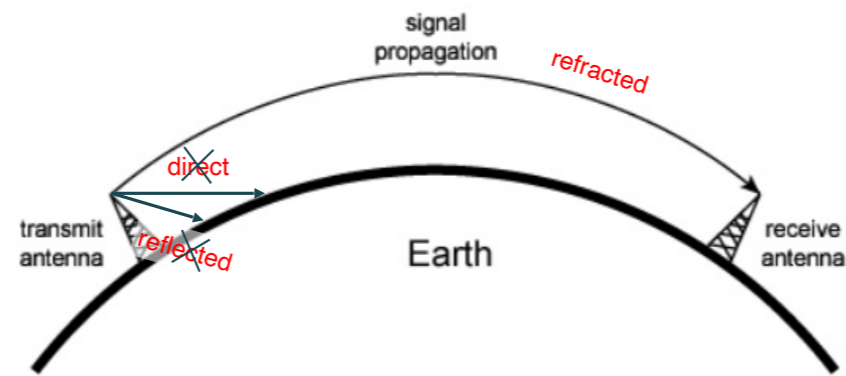
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1 to 10 mm	EHF				



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■ ELF/VLF/LF/MF: Ground wave propagation (3 kHz < f < 3 MHz)



[1]: SWIC 2024 – STCE, RNLAf & KNMI



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Ground wave propagation is the combination of direct, reflected and refracted waves.

As direct and reflected waves are blocked by the earth, for communication beyond the horizon only the refracted wave is able to propagate. This wave we call the surface wave.

As we are interested in communication beyond the horizon the surface waves are called ground waves from now on.

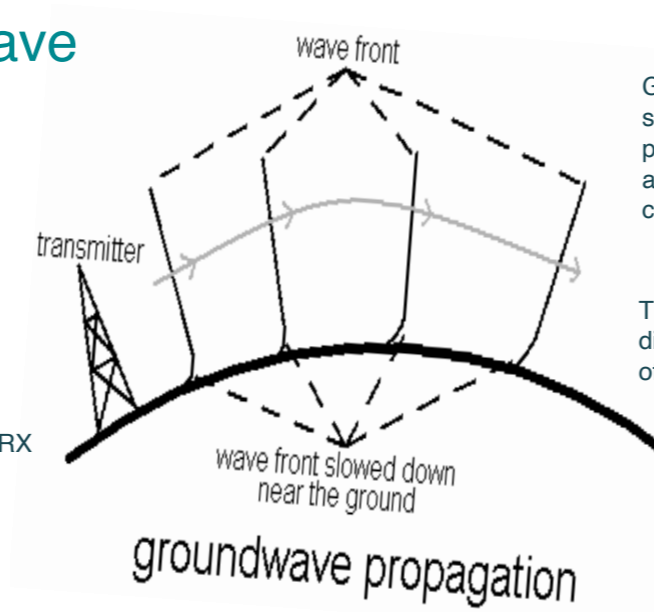
Ground wave propagation works optimal between 3kHz and the first few MHz. Higher frequencies are absorbed by the earth, lower frequencies prefer waveguides.

https://en.wikipedia.org/wiki/Ground_wave_propagation

Ground wave

Higher frequency
↓
More ground wave
attenuation

More TX power
↓
More power arriving at RX



Ground waves are only supported in vertical polarization, so by vertical antennas. The horizontal component attenuates quickly.

There is also the component of diffraction around the curvature of the earth

[1]: SWIC 2024 – STCE, RNLAf & KNMI



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The working principle is quite complex. Essentially, there is a component of the wave that gets trapped on the interface between the air and the surface. Complicated math describes that this electrical field is *tilting over* (so it is not entirely vertical) at said interface. The result is that a part of the wave gets aimed towards the soil, where it loses energy. The higher the frequency and the lower the conductivity of the soil the more the vector of the electric field tilts over, and the more energy it loses to the soil. Additionally, the wave also diffracts around the surface of the earth.

https://en.wikipedia.org/wiki/Ground_wave_propagation

■ Ground waves

- Suffer from obstacles such as mountains, which disrupt the curvature concept explained before
- Suffer from rough terrain or terrain with bad conductivity

Therefore:

- Ground wave propagates excellently over sea

■ Propagation mechanism matrix

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■ Propagation mechanisms on ELF and VLF

SUMMARY:

- Excellent ground wave propagation
 - Attenuation becomes impactful at longer distance
- Waveguide propagation
 - Waveguide between Earth and the D layer of the ionosphere
 - Waveguide mechanism is dominant over ground wave at long range
 - Only on ELF and VLF
 - Increased D layer ionization improves propagation

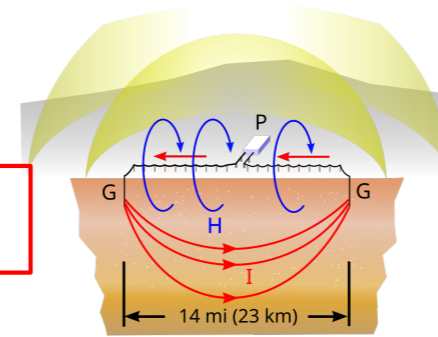
■ Applications

- Radio navigation
- Time beacons
- Secure military communications (submarine)
- Communication within mines (ULF, VLF, LF)

■ Challenges on ELF/MLF

- Very expensive transmit equipment:
 - Antennas are huge...
 - But still electrically short ($\ll \lambda/4$)
 - Therefore very inefficient:
 - Megawatt input powers required
 - Few watts of realized output power
 - For intra-mine communication, close by allows magnetic field use
- Receive equipment is easier
 - Natural noise level \gg receiver internal noise level
 - So much margin for amplification by receiver
 - So receive antenna can permit to be horribly matched
 - Usually ferrite loop antennas are used

Wavelengths of 100 km and up resp. 10 km and up



■ Summary: ELF & VLF

- **Waveguide** and **ground wave** are dominant propagation principles
- Signal detectable through a limited depth of seawater → submarines
- Transmit antenna challenges

Frequency band

LF - MF

■ Propagation mechanism matrix

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■ LF and MF

Frequency too high for waveguide propagation
Frequency too low for skywave
→ Only groundwave applies significantly

Usage:

LF: AM broadcasting, navigation, time signals

Functionally spoken, higher MF (1,5 MHz or 2 MHz and up) could be considered HF



■ VLF, LF and MF antennas



[1]: SWIC 2024 – STCE, RNLAf & KNMI

VLF and LF suffer from similar challenges as ELF antennas, albeit not as extreme.

MF antennas become more feasible to implement efficiently, requiring powers in the kW order of magnitude.

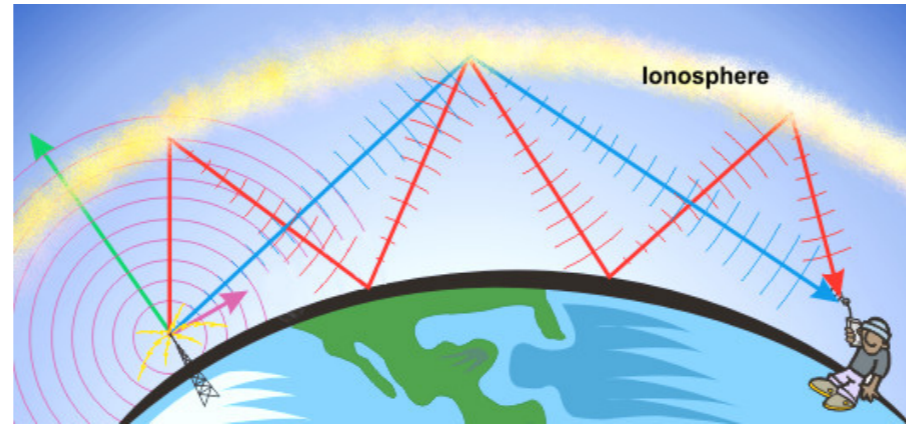


[1]: SWIC 2024 – STCE, RNLAf & KNMI

Frequency band

HF

MF/HF: Skywave propagation



[1]: SWIC 2024 – STCE, RNLAf & KNMI



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Parameters of ionospheric layers

CUF = Critically Useable Frequency

- Which frequency gets reflected by the plasma?
- Directly related to the plasma's charge density

MUF = Maximum Useable Frequency

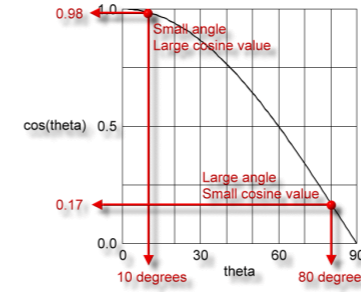
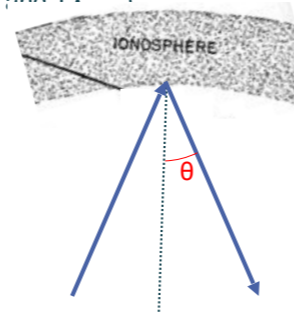
- Highest frequency useable for a certain link
- Depends on the geometry of the radio path (layer height, location of RX and TX)

$$MUF = \frac{CUF}{\cos(\theta)}$$

Frequency too high for MUF?

- Wave 'breaks' through the layer

Optimum frequency for stable transmission: 0,8 x MUF



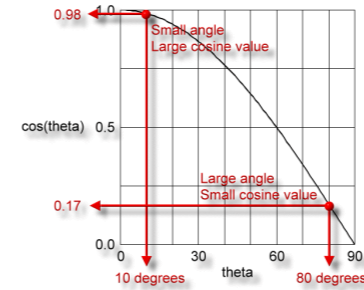
E. A. Zobel, "Inclined plane | Zona Land Education," Zona Land Education, [Online]. Available: <http://zonalandeducation.com/mem/physical/mechanical/forces/inclinedPlane/angleAndComponents/angleAndComponents.html>. [Accessed 10 10 2022].

■ What to expect from MUF/CUF ratio?

Distance over ground [km]	Typical MUF / CUF for F2 layer
400	1,2
1000	2
3000	3 – 3,5

For a 3000 km link, multipliers of 2,5 – 4 occur

Check out [Ionosphere and Space Weather | Royal Meteorological Institute](#) and look for the M(3000) parameter to see the parameter evolving throughout time.



E. A. Zobel, "Inclined plane | Zona Land Education," Zona Land Education, [Online]. Available: <http://zonalandeducation.com/inclinedplane/forces/inclinedPlane/angleAndComponents/angleAndComponents.html>. [Accessed 10 10 2022].

■ Parameters of ionospheric layers

LUF: Lowest Useable Frequency

- D-layer attenuates waves passing through $\sim 1/f^2$
 - Too much attenuation? Signal lost.
 - More power, more chance to get the necessary amount through

Layer height

→ Has impact on the angle with which the wave impinges on the layer

■ Parameters of ionospheric layers

- **Critically Useable Frequency (CUF):** What is, at this location, the max frequency that comes back when radiating upwards?
- **Maximum Useable Frequency (MUF)** of a layer: What is, for this location of the transmitter and this location of the receiver, the max frequency that is reflected by this layer and so ends up at the receiver?
- **Lowest Useable Frequency (LUF):** What is, for this location of the transmitter and this location of the receiver, the lowest frequency that gets through enough power so my receiver hears it?
- **Layer height.** Mind that there's more than 1 layer the wave could refract against.

■ Frequency considerations

■ Radiating at high angle

Scenario:

- Conversation partner is close by (tactical situation)
 - Conversation partner is behind obstacles (hills, ...)
- The **incidence** angle of your wave **should be nearly vertical** =

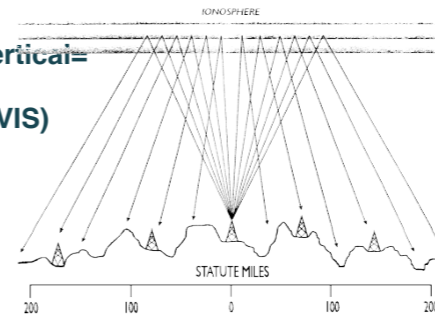
Such scenarios, we call **Nearly Vertical Incidence Skywave (NVIS)**

Quiz:

Radiating upwards means MUF is:

1. close to CUF
2. significantly higher than CUF
3. significantly lower than CUF

$$MUF = \frac{CUF}{\cos(\theta)}$$



Radiating at high angle

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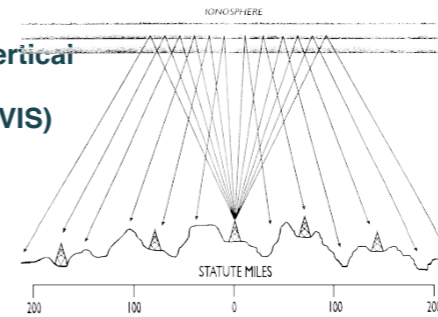
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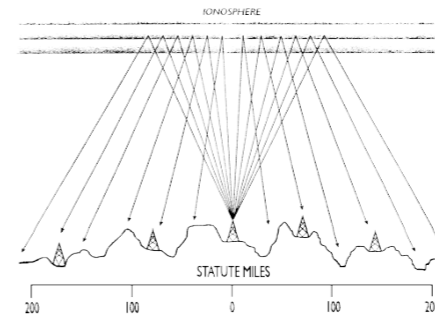
$$MUF = \frac{CUF}{\cos(\theta)}$$

CUF only tells something about the state of the *local* ionosphere.



■ Near Vertical Incidence Skywave (NVIS)

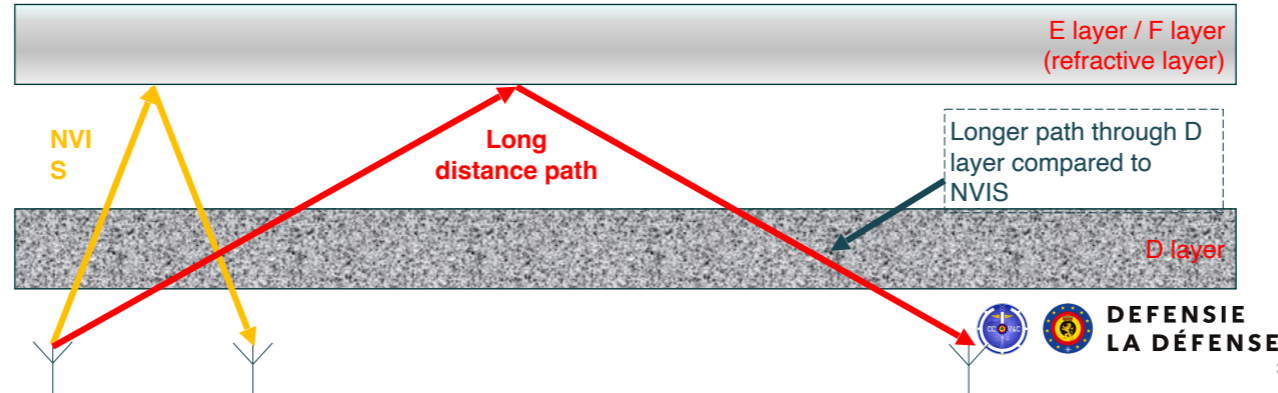
- Useful in hilly/mountainous/urban terrain
- Limited range
- Frequency should not exceed CUF (think of optimum freq.)
- Similar signal quality in targeted area
As opposed to line of sight-comms or ground wave comms, that suffer from obstacles and different soil types (causing variations in signal strength).



Influence of the D layer on skywave

The longer the distance over which the signal is traversing the D layer, the more attenuation accumulated.
→ NVIS is less attenuated than long distance link due to shorter path through D layer
→ Multiple hops lose more power due to multiple D layer crossings

The D layer attenuates signals proportional with $1/f^2$



■ Frequency selection

→Low frequency for NVIS scenarios

→Higher frequency for long distance

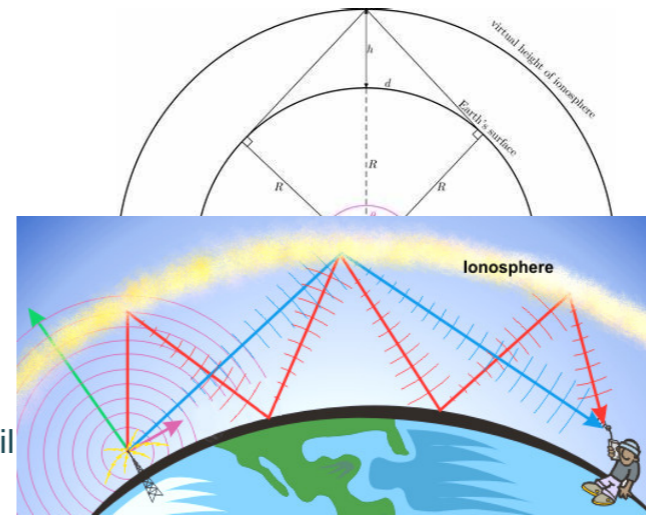
Multiple hops

Due to simple geometry, the range of a single hop is limited.

However: the ground reflects a portion of the wave as well.

→ A decent portion of signal reflects towards the ionosphere, resulting in multiple hops.

→ Degree of energy loss depends on soil type.

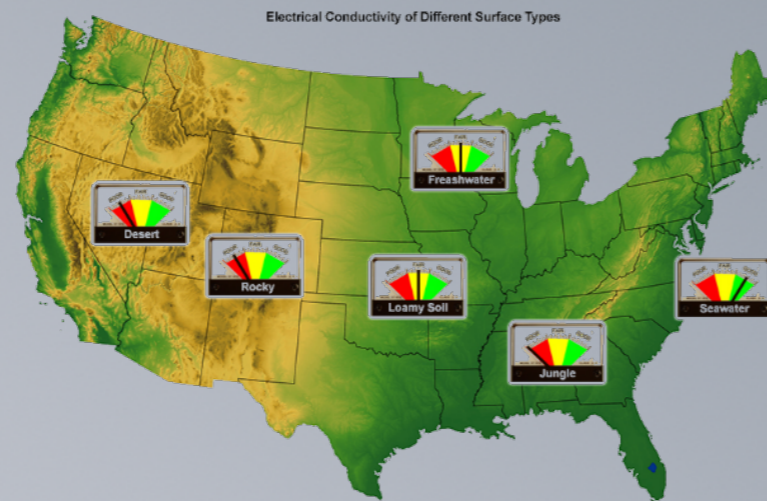


[1]: SWIC 2024 – STCE,
RNLAf & KNMI



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Multiple hops – soil type



Poor reflectors:

- Rock
- Desert
- Jungle

Good reflectors:

- Sea water
- (Freshwater)



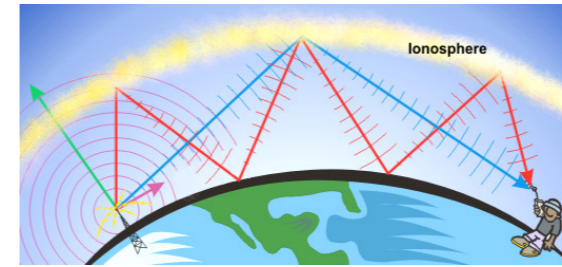
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■ Multiple hops – frequency window

The state of the ionosphere is location dependent.

Every 'hop' touches the ionosphere layers and the ground on a different location, therefore imposing its own limits on MUF and LUF, call it a "frequency window"

- Some multi-hop links are challenging, due to very small or inexistent frequency window overlaps
- North – South link is much harder than East-West link



[1]: SWIC 2024 – STCE
RNLAf & KNMI



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Skip zone

Quiz:

Suppose CUF is 3 MHz for the entire region.

You are allocated only use of 4 MHz.

Can you reach a receiver who is:

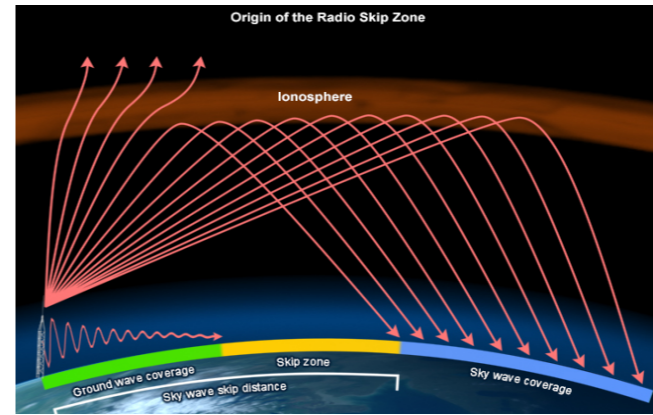
- 1000 km away?
 - Yes: MUF is definitely larger than 3 MHz for this link
- 100 m away?
 - Yes, line of sight
- 10 km away?
 - Probably yes: ground wave
- 100 km away?
 - Ground wave became too weak
 - MUF is not much higher than CUF!

No link!

There is a zone you cannot reach:
the **skip zone**

$$MUF = \frac{CUF}{\cos(\theta)}$$

Remember: at 1000 km away,
usually the MUF is about 2x the
CUF



Coffee break?



PREPARE KWT

[Ireland Kiwi#1ei6iz](#)

[VOACAP Online for Ham Radio](#)

[QSO/SWL real time maps and lists](#)

[International Beacon Project Azimuthal Map](#)

14100 kHz – 21 m
18110 kHz – 17 m
21150 kHz – 15 m
24930 kHz – 12 m
28200 kHz – 10 m



The careful reader notices that 28200 kHz has a wavelength that is actually somewhat larger than 11 m. It is however part of the radio amateur band that is commonly referred to as "the 10 m band". The same goes up for 21150 kHz being closer to 14 m.

■ Frequency selection

■ What to expect from CUF at medium latitude

Dependent on:

- Time of day
- Season
- Solar cycle
- Other effects, such as space weather, volcanic events, ...

Can range from 1,5 MHz to 10 MHz and up

<https://giro.uml.edu/IRTAM/>

<http://ionosphere.meteo.be/ionosphere/ionosonde/index.php>



■ Typical CUF values at medium latitude

Winter solar minimum

- Day: 5 MHz
- Night: 2 MHz
- Lowest just before morning
- Quickly rises from sunrise until a good hour later

Winter solar maximum

- Day: 12 MHz
- Night: 3 MHz
- Lowest just before morning
- Quickly rises from sunrise until a good hour later

→ More ionization, higher CUF

All numbers are purely indicative

They furthermore strongly depend on solar activity and space weather (SWx)

■ Typical CUF values at medium latitude

Summer solar minimum

- Day: 3 MHz
- Night: 5 MHz
- Lowest just before morning
- Modest deviation through day-night cycle

Summer solar maximum

- Day: 8 MHz
- Night: 6 MHz
- Lowest just before morning
- Modest deviation through day-night cycle

→ More ionization, higher CUF

All numbers are purely indicative

They furthermore strongly depend on solar activity and space weather (SWx)

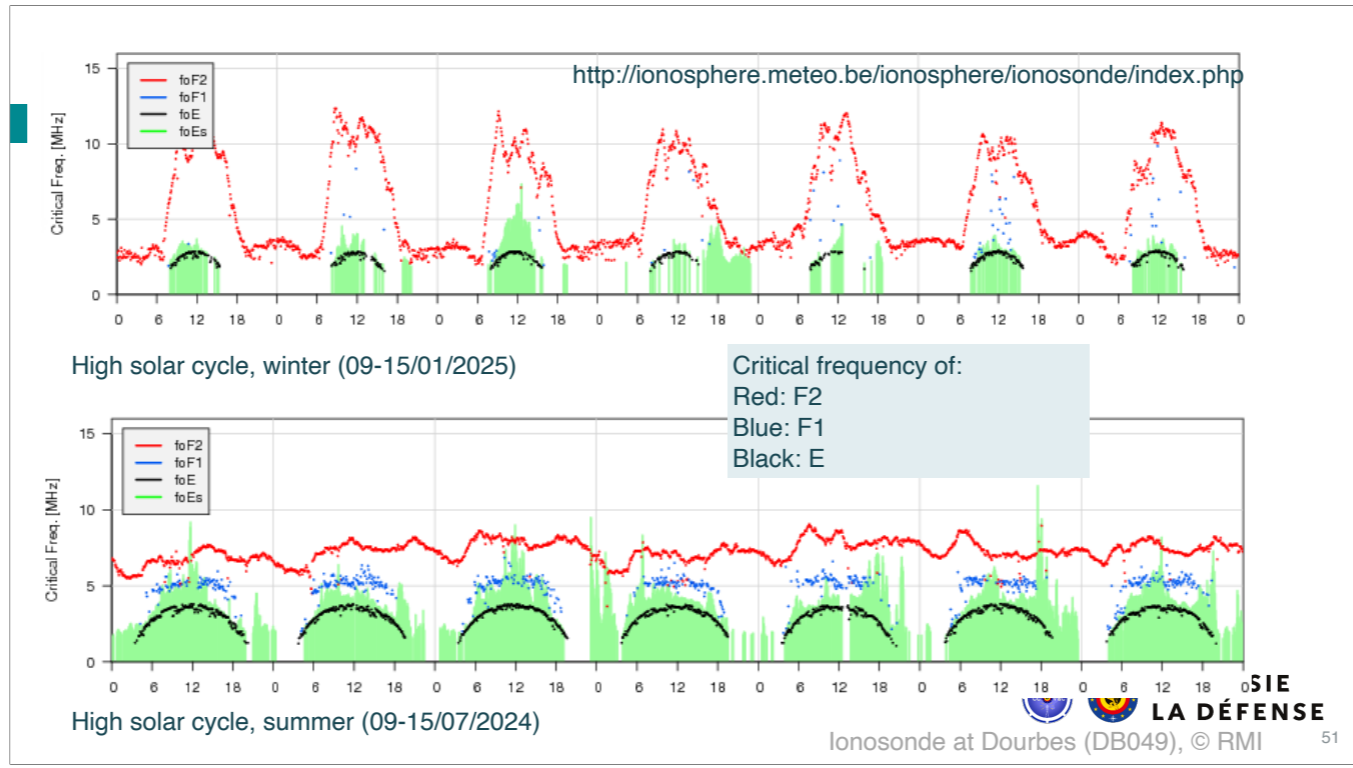
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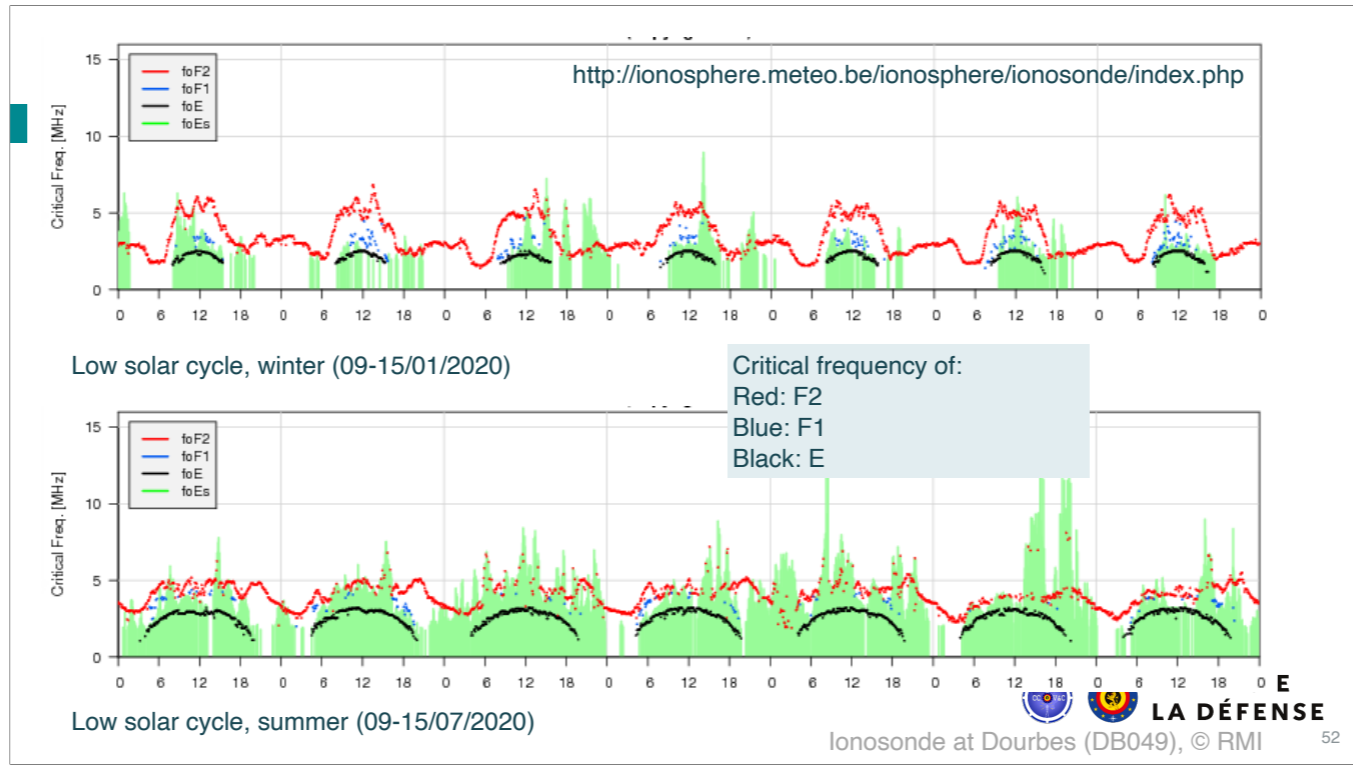
Ionisation:

- Day and night is a clear difference (day is obviously more ionized)
- Usually somewhat more ionisation (higher MUF) in summer
- More ionisation during solar maximum

Quite logical:

- Night: no sun there
- Winter: sun is low, so less sun per square meter atmosphere
- Less solar activity (so less ionization) during solar minima





■ Quiz: Why not always use low frequencies?

- Frequency availability
- The lower the frequency, the more the ionosphere's D layer absorbs the wave
 - Skywave under 1 MHz is quasi never useable
 - Usually, the lowest useable frequency for NVIS skywave is between 1,5 MHz and 2 MHz

■ Polarization

As a result of Earth's magnetic field, a left-hand circularly polarized signal is refracted differently than a right-hand circularly polarized signal.

→ They end up at a somewhat different location

Our antennas are no lasers: they have a certain beamwidth, so you'll receive both components from somewhere.

Two ways to look at it:

→ The LHCP wave you received comes from a somewhat different angle than the RHCP wave

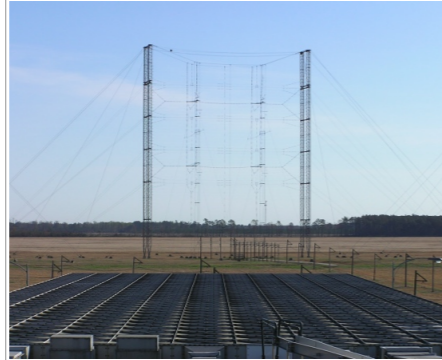
or:

→ The LHCP takes a path with a different length than the path of the RHCP wave

! Note that a linearly polarized signal is just the sum of a LHCP and a RHCP component !

Since the ionosphere 'pulls' LHCP and RHCP apart, for a skywave path, the polarization of the antennas doesn't really matter...

HF antennas



[1]: SWIC 2024 – STCE, RNLAf & KNMI



[1]: SWIC 2024 – STCE, RNLAf & KNMI



■ Excercise

Let's radio!

[Ireland Kiwi#1ei6iz](#)

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24930 kHz – 12 m
28200 kHz – 10 m



The careful reader notices that 28200 kHz has a wavelength that is actually somewhat larger than 11 m. It is however part of the radio amateur band that is commonly referred to as "the 10 m band". The same goes up for 21150 kHz being closer to 14 m.

■ Specials

■ Specials

- Long path propagation
- Short Wave Fades
 - Polar Cap Absorption
- Eccentric layer usage
 - E layer propagation
 - Sporadic E
 - Chordal modes
 - Ducting
 - Greyline propagation
 - Combinations of paths
- Traveling Ionospheric Disturbances
- Low latitude ionosphere
 - Transequatorial propagation
 - NVIS at low latitudes



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■ The radio path

Note: One cannot choose to “go into multiple hop mode” or “select” one of the special cases.

The ionosphere is what it is.

The signal is radiated by the TX and ends up where it ends up.

We aim to select the proper frequency and power so our intended receiver hears us.

The HF signal is reached in an immense area!

→ Your adversary will probably hear you too

→ Tactical cells of multiple 100's of kms

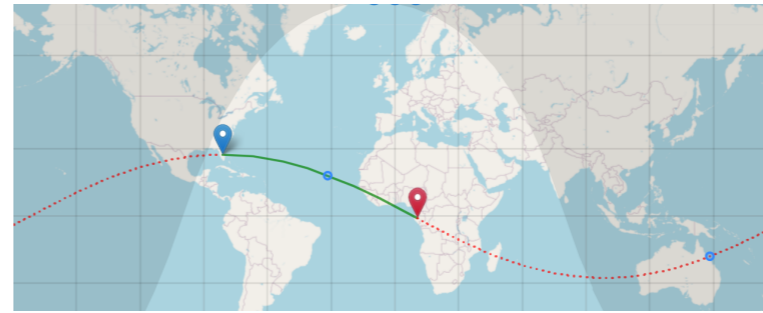
→ Note that the SOS of the Moskva on 3,5 MHz has been heard by Belgian radio amateurs



■ Long path propagation

The “short path” between TX and RX is not the only solution in which the RX is reached... (green line)

There is also a “long path”, in the opposite direction of the short path. (red dotted line)
→ Arrives a little later
→ Existence and strength depend on propagation conditions along the long path



VOACAP: <https://www.voacap.com/hf/>
© OpenStreetMap contributors



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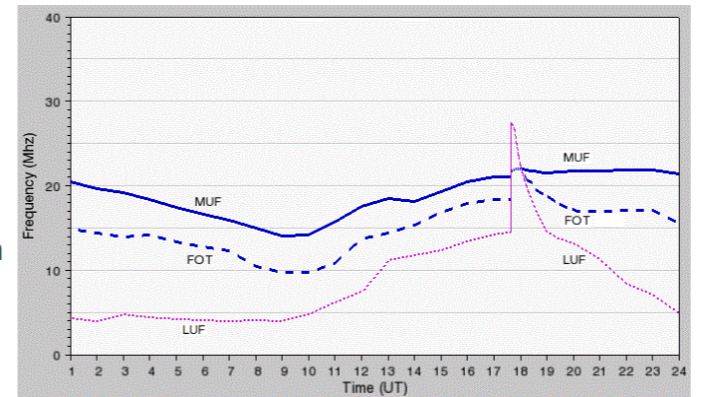
Short Wave Fade

As discussed in one of the previous sessions

MUF and LUF are properties of a radio path

When for a certain link $MUF < LUF$, that path supports no skywave. This is called a Short Wave Fade (SWF) or a Radio Blackout.

- MUF might dive sharply during geomagnetic storms.
- Heavy ionization of the D layer, such as during big flares or proton events, may drastically increase LUF



[1]: SWIC 2024 – STCE, RNLAf & KNMI

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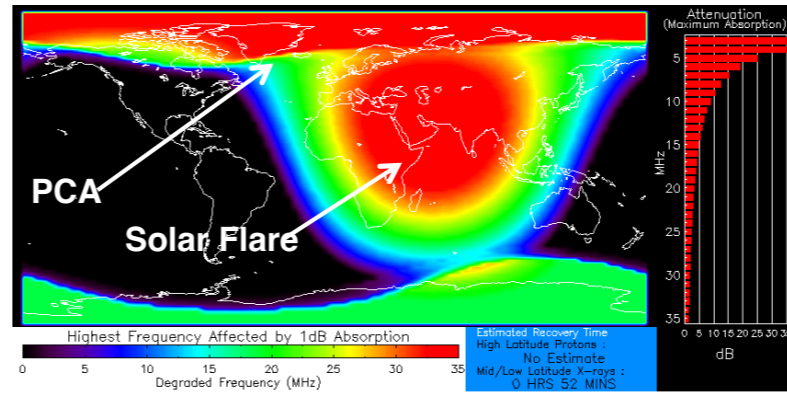
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Short Wave Fade

As treated in one of the previous sessions

Note: Flares may last some minutes up to a few hours

Polar Cap Absorption may even last up to 10 days



Moderate X-ray flux
Product Valid At : 2015-06-25 08:17 UTC

Normal Proton Background
NOAA/SWPC Boulder, CO USA

[1]: SWIC 2024 – STCE, RNLAf & KNMI



■ Polar Cap Absorption

As treated in one of the
previous sessions

Many SWx events (geomagnetic storms, proton events, ...) cause particle precipitation over the poles, ionizing the D layer.

- May last up to 10 days, depending on SWx event
- Strength is highly variable, dependent on the current amount of matter being deposited by the SWx event

Note that this may even happen on the perpetually dark poles in the winter, as the driving mechanism is not solar radiation.

What to do?

- Find a relay station located further away from the poles that can be contacted on a higher frequency

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■ E layer propagation: what?

E layer is commonly significantly less ionized than the F layers.

Typical E layer CUF for Belgium is:

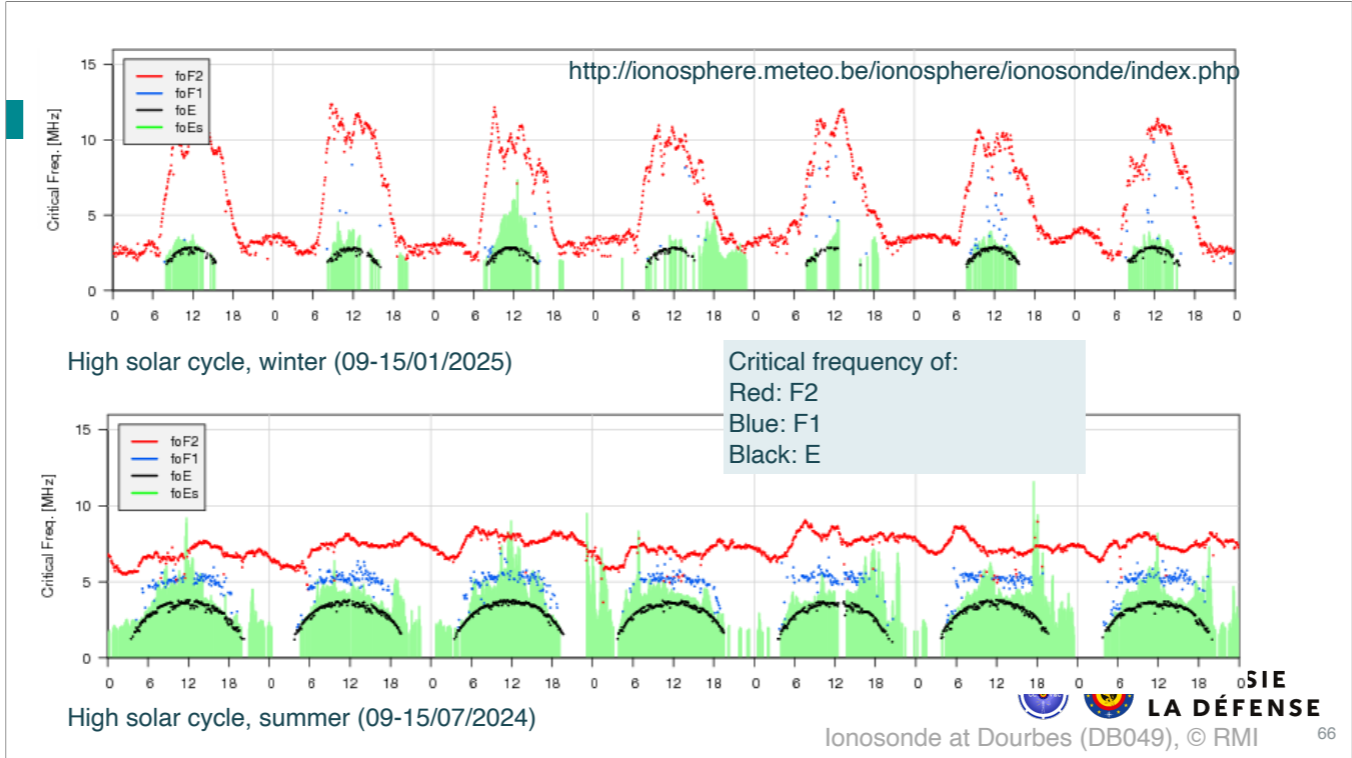
- Slightly below 2 MHz close to sunrise/sunset
- Rises to 2,5 MHz in low solar cycle winter, 3,5 MHz in high solar cycle summer.

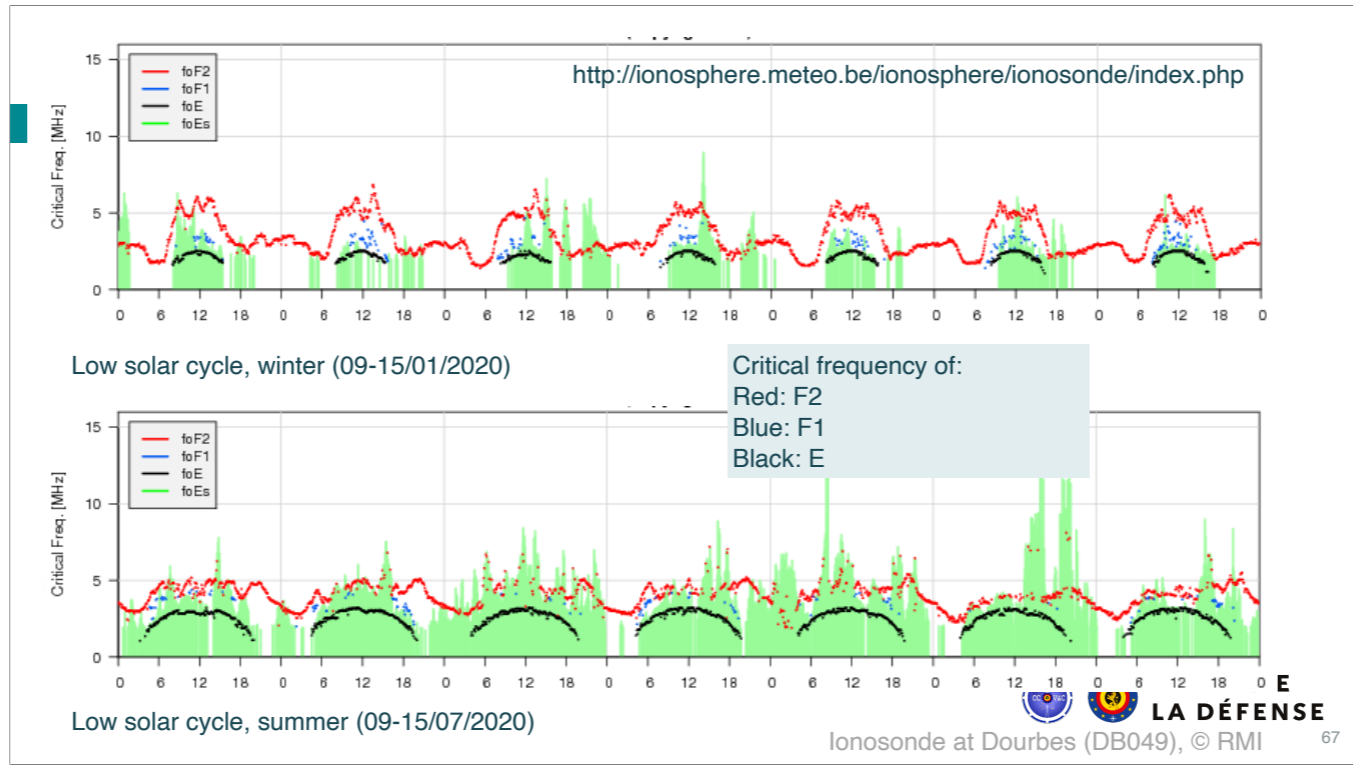
The E layer disappears at night.

<http://ionosphere.meteo.be/ionosphere/ionosonde/index.php>



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E layer propagation: be mindful

Low-angle path → MUF >> CUF

→ E layer MUF for this angle might be rather large

→ Refraction against the E layer instead of the F layer

→ Due to low E layer altitude, hop could end up closer by than intended

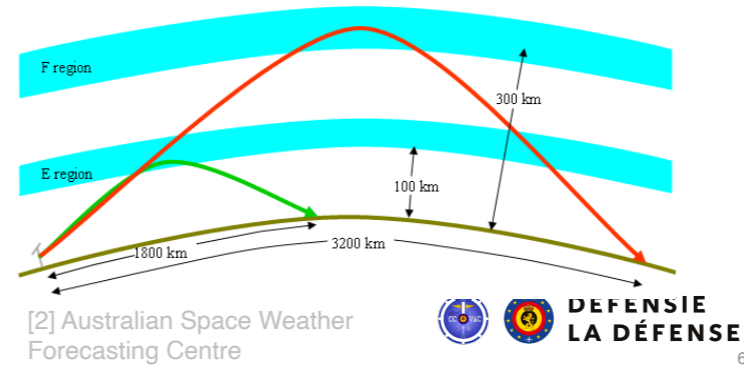
→ This may be the aim!

Decrease of the tactical cell size:

Intended NVIS for close by

Long distance radiation against
E instead of F

Antennas intended for NVIS
mainly radiate upwards

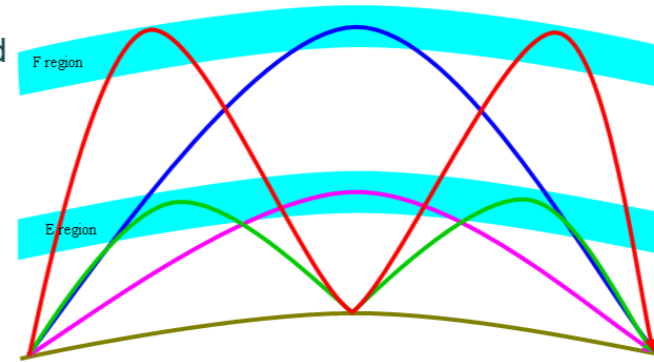


Combinations of all

The ionosphere is what it is.
The signal is radiated by the TX and ends up where it ends up.

For certain ionization profiles, this could mean:

All of them have a geometric path to the receiver.



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■ A special within the specials: sporadic E

■ Sporadic E: what is it?

Unexpected (and often severe) ionization at E layer altitudes due to:

- Meteors burning up, leaving ionized trails
- Metallic particles aggregating together in thin layers due to interplay of different physical phenomena
 - Volcanic eruptions
 - Rocket launches
 - ...

■ Sporadic E

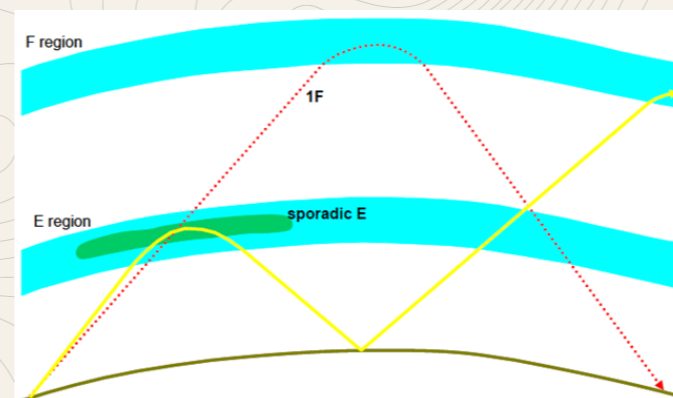
Abbreviated as Es

Altitudes of 90-140 km

Can occur night and day

Quite localized: regions of a few km's wide, to 100's of kms wide

Effects dissipate after ten minutes to a few hours



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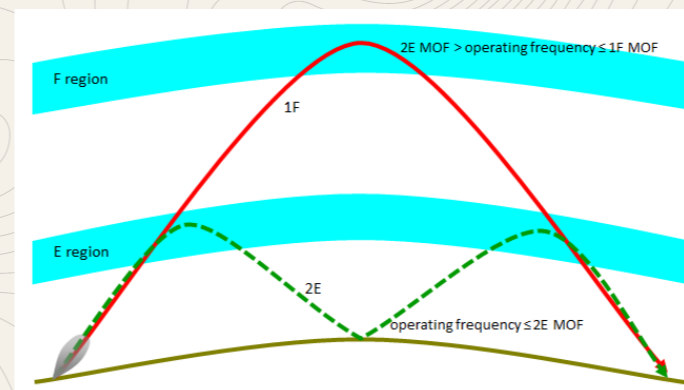


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■ Sporadic E: blanketing

If $MUF(F) < MUF(E_s)$, all reflections on the path will occur against the E_s .

Ionograms show blanketing:
Nothing refracts against the F layer, everything has been refracted against the E_s already



[2] Australian Space Weather Forecasting Centre

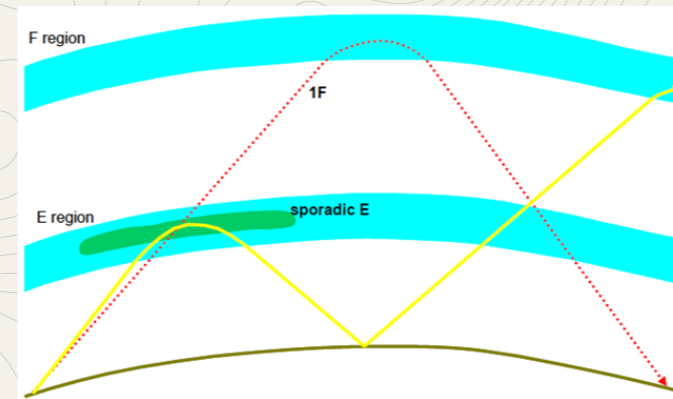


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■ Sporadic E

Ionization can be extreme: even refracting UHF

Es can also be partially transparent, allowing downward passage of a part of waves just reflected against the F
→ May lead to weak or fading signals as the layer evolves



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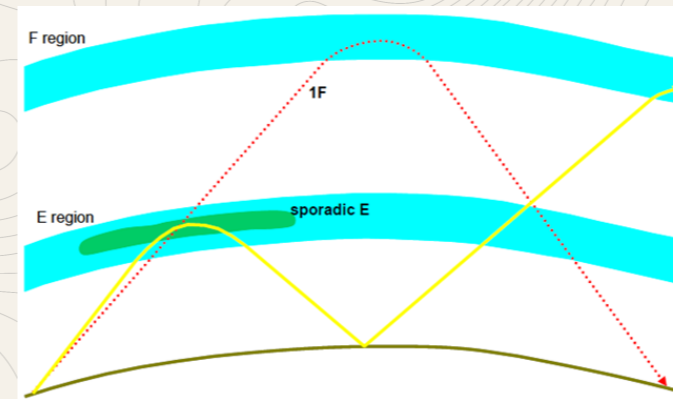


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■ Sporadic E

More hops increase signal attenuation:

- More bounces against the ground
- More passes through D layer



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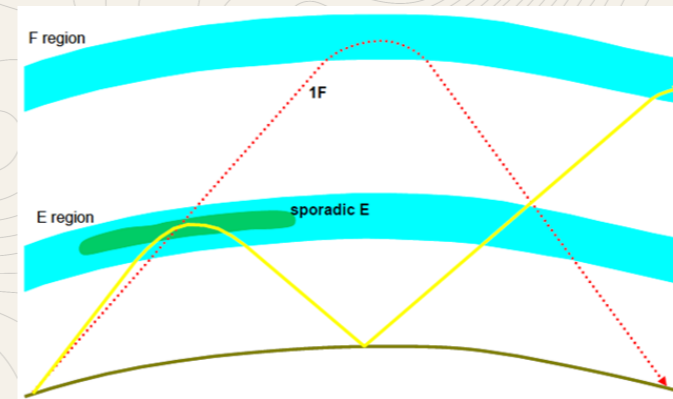


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■ Sporadic E

The propagation path is not as anticipated

A TX on the right might not be able to reach a RX on the left side (or vice versa)



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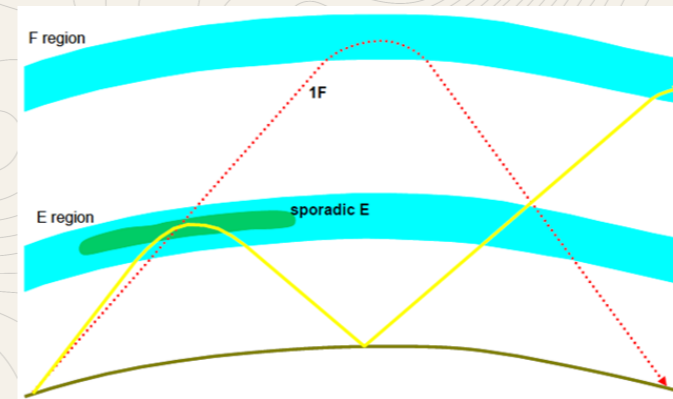


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■ Sporadic E

At **moderate** and **low** latitudes: more prevalent during **day** and **evening**

At **high** latitudes: more common at **night**, and especially when the ionosphere is **disturbed**



[2] Australian Space Weather Forecasting Centre

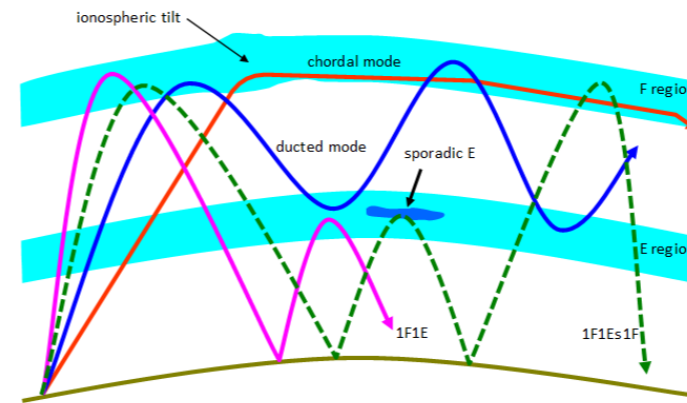


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Chordal mode

Chordal mode:
Accidental ionospheric tilt creates a geometric path where the wave keeps hitting the layer at a very steep angle

- No extra hops (so no D layer passage: ground reflections...)
- Only comes down at another irregularity (hence completely coincidental)
- Superb signal quality over extreme distances (up to worldwide) since very little power got lost



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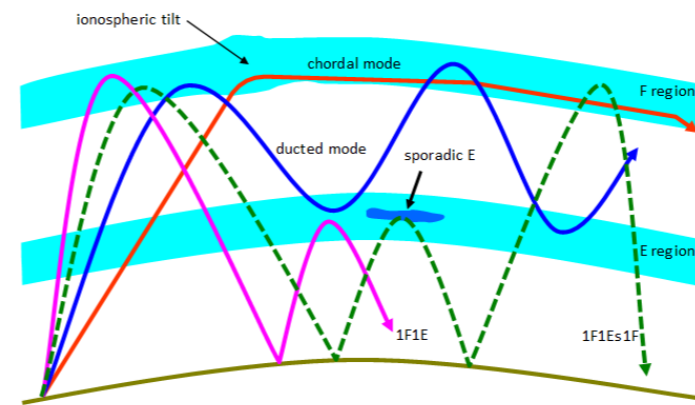
Ducting

Ducting:
MUF(E) on the left < freq of operation <
MUF(F)

AND

MUF(E) on the left < freq of operation <
MUF(E) on the right

- Waveguide behavior between E and F layers
- No extra hops (so no D layer passages, ground reflections...)



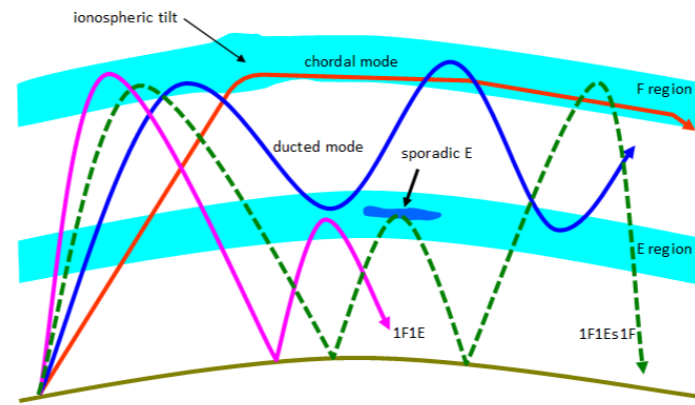
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Other exotics

Note the other paths drawn on the figure. Dependent on the local ionizations, this can happen!



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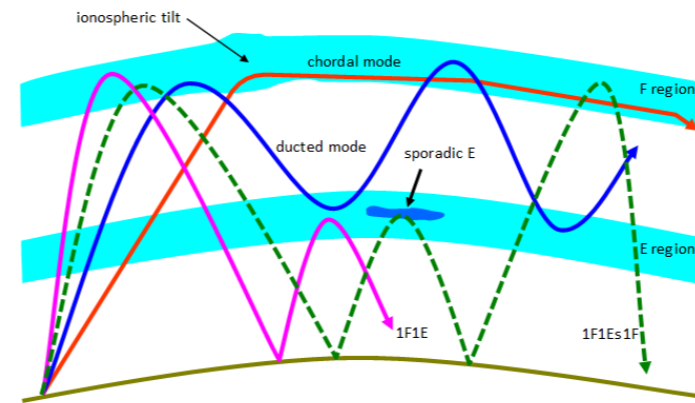
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■ Greyline propagation

The F layer 'cups' a little on the edge between day and night

→ Deliberate aim to find a chordal mode

→ Many paths that should be unfeasible work during around an hour before sunrise or after sunset



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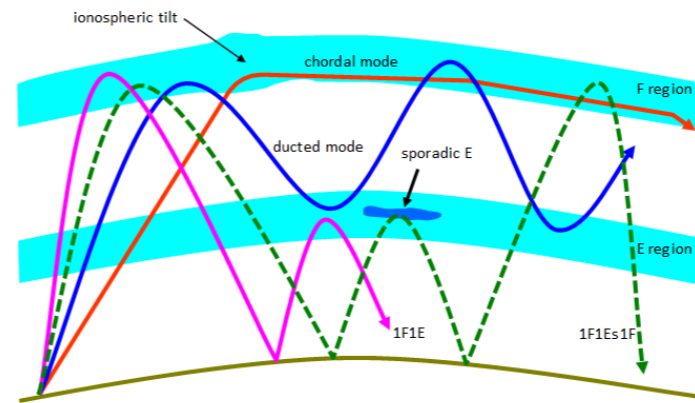
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Greyline propagation

Evening:
Decreasing ionization above your head, but not yet at a low angle since that region is still well-ionized by the sun?

No more D layer above your head, only at RX

- Radiate at said low angle, getting under the still well-ionized F
- Much better signal quality



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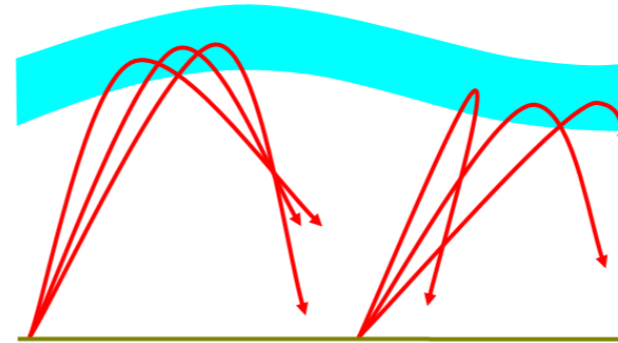
■ Traveling Ionospheric Disturbances (TIDs)

Significant fading may occur due to TIDs

→ Multiple geometric paths exist between TX and RX, which may exhibit very different travel times or a significant frequency shift, but have similar signal strength.

→ Signal gets hard to interpret, causing fading.

→ Effects last about 10 minutes and up



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■ Ionosphere at low latitudes

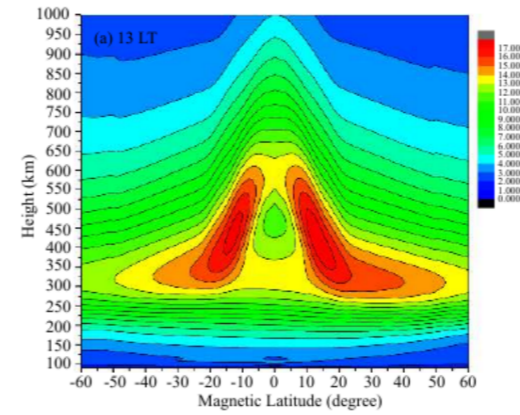
Remember the Equatorial Anomaly at low geomagnetic latitudes

Higher ionization than typical F layer at mid latitudes

Maximum ionization at lower altitude than mid latitude F

→ Ionosphere 'bulges' downward!

→ Geometric implications



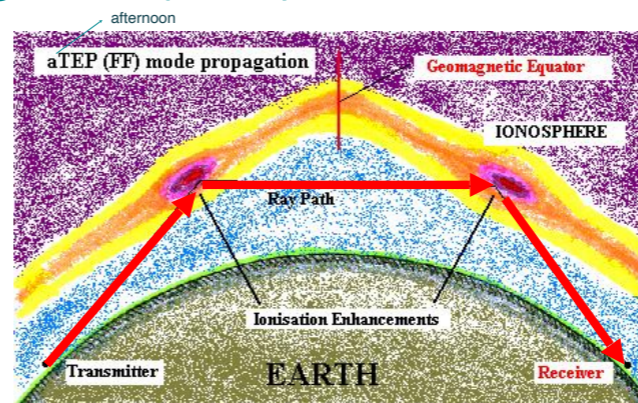
Tobias Verhulst, Role of the ionosphere and SWx in Mil Comms, 2025

Transequatorial propagation (TEP)

Can occur during the afternoon, when the anomaly is sufficiently built up.

Bulges in the equatorial anomaly:

- Allow for a chordal mode-like propagation
 - For long links (5000-6500 km), symmetric along the equator
 - In the North \leftrightarrow South direction
 - Without passage through the D layer
- Wave hits ionosphere with a very shallow angle \rightarrow MUF typically 15 to 25 MHz **above typical values**
 - MUF of 60 MHz has been observed



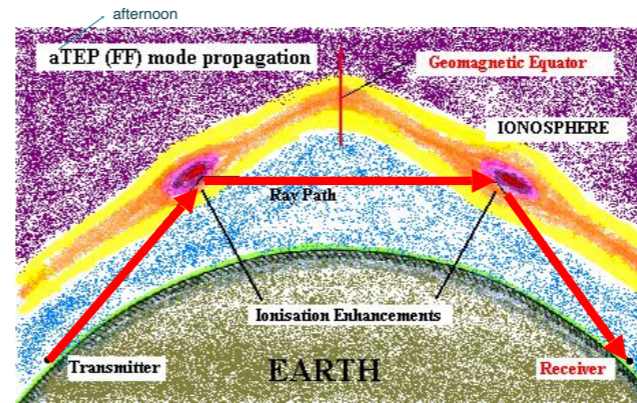
[2] Australian Space Weather Forecasting Centre

Transequatorial propagation (TEP)

Evening TEP exists as well:
Heavily ionized bulges dissipate in the evening, leaving behind very irregular structures (plasma bubbles).

These structures may support TEP with even higher frequencies, but the path is extremely irregular, causing severe fading and very strong distortion.

In practice, eTEP should not be considered fit for communication.



[2] Australian Space Weather Forecasting Centre

NVIS at low latitudes

Under the plasma fountain:

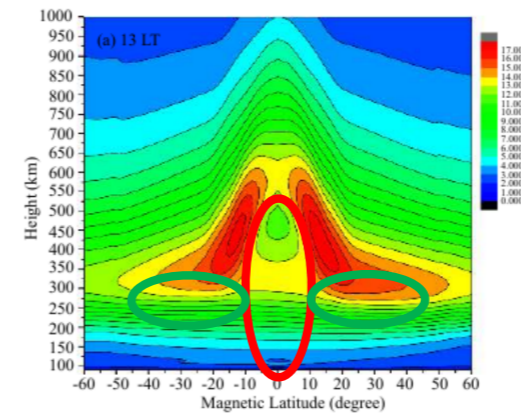
Plasma fountain contains irregular and upward streaming patches of ionized material

→ Not a homogeneous environment

→ Waves radiated into this fountain scatter to all directions



Under the "bulges":
Excellent ionization!



Tobias Verhulst, Role of the ionosphere and SWx in Mil Comms

■ Propagation mechanism matrix

Wavelength Range	Abbreviation	Waveguide	Ground wave	Skywave	Line of Sight
>100 km	ELF				
10 to 100 km	VLF				
1 to 10 km	LF				
100 to 1000 m	MF			Higher MF	
10 to 100 m	HF		Lower HF		
1 to 10 m	VHF				
10 to 100 cm	UHF				
1 to 10 cm	SHF				
1 to 10 mm	EHF				

**Well
actually...**

Note that tropospheric ducting is strictly spoken not skywave since it doesn't refract against the ionosphere

Propagation mechanism matrix

Wavelength Range	Abbreviation	Waveguide	Ground wave	Skywave	Line of Sight
>100 km	ELF				
10 to 100 km	VLF				
1 to 10 km	LF				
100 to 1000 m	MF			Higher MF	
10 to 100 m	HF		Lower HF		
1 to 10 m	VHF	Tropospheric ducting			Well actually...
10 to 100 cm	UHF				
1 to 10 cm	SHF				
1 to 10 mm	EHF				

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Note that tropospheric ducting is strictly spoken not skywave since it doesn't refract against the ionosphere

Propagation mechanism matrix

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10 to 100 cm	UHF				
1 to 10 cm	SHF				
1 to 10 mm	EHF				

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Note that tropospheric ducting is strictly spoken not skywave since it doesn't refract against the ionosphere

■ Propagation mechanism matrix

Wavelength Range	Abbreviation	Waveguide	Ground wave	Skywave	Line of Sight
>100 km	ELF				
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1 to 10 km	LF				
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10 to 100 m	HF		Lower HF		
1 to 10 m	VHF				
10 to 100 cm	UHF				
1 to 10 cm	SHF				
1 to 10 mm	EHF				

■ In case all else fails

[RFC 1149: Standard for the transmission of IP datagrams on avian carriers](#)



■ Q&A