CC V&C
Dries Van Baelen, Dr. Ing. (CIV)

January 29th, 2025

DEFENSIE
LA DÉFENSE

Radio communication

This session

- Use of the ionosphere for radio communications
- Practical implications

DEFENSIE
LA DÉFENSE

Lecturer and credits

Your lecturer:
Dries Van Baelen *Belgian MoD, Directorate General of Material Resources*

Slideshow assembled from the contributions of:
[1] 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

DEFENSIE
LA DÉFENSE

Outline

- Recap on ionospheric layers
- Propagation types

- VLF
- HF
- SATCOM

DEFENSIE
LA DÉFENSE

DEFENSIE
LA DÉFENSE

Recap on ionospheric layers

Ionospheric layers

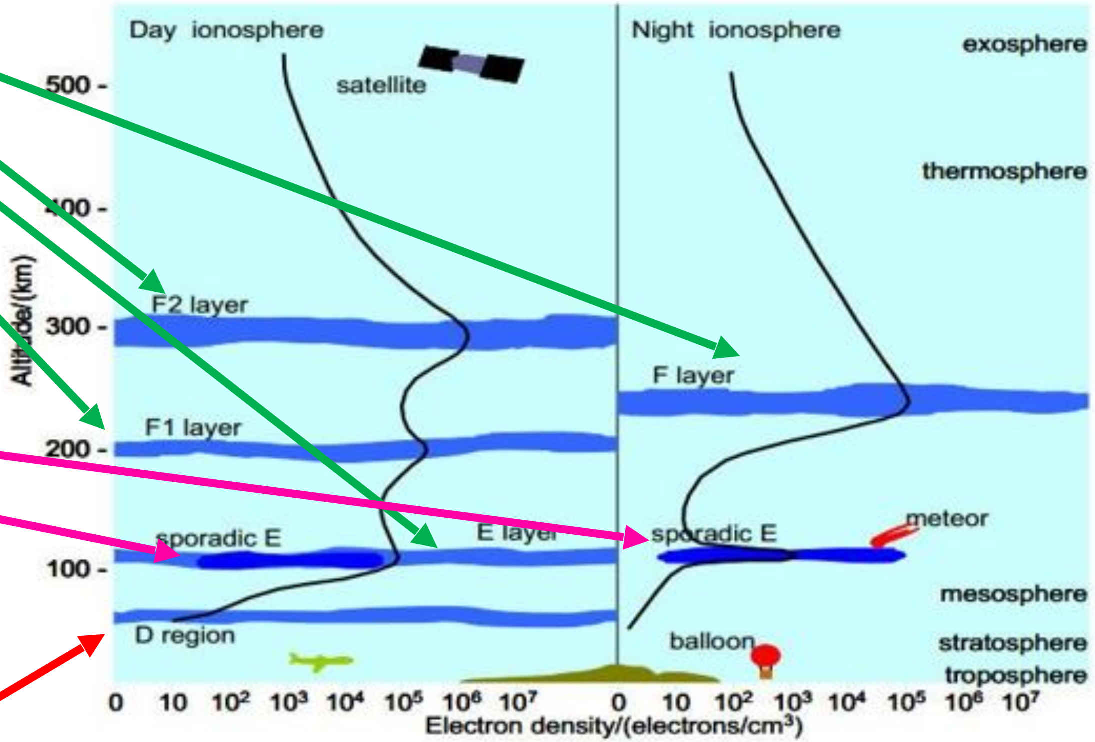
- D layer
  - Waves entering D layer attenuate corresponding to a factor ~ $1/f^2$
  - Typically absorbs frequencies up to 1,5 MHz – 2 MHz
  - Only present during the day
  - 60-80 km altitude
- E layer
  - Typically refracts frequencies up to 2 MHz – 4 MHz
  - Only present during the day
  - 100 km altitude
- F layer
  - Typical refraction strongly dependent on diverse criteria (see later)
  - Strong during the day, weaker at night
  - Often desired layer for communications
  - 200-400 km altitude

Ionospheric layers

These are the desired ones

This is the unexpected one

This is the one we often don't like



[2]: Australian Space Weather Forecasting Centre

DEFENSIE
LA DÉFENSE

DEFENSIE
LA DÉFENSE

Propagation types

Propagation types

- Waveguide
- Groundwave
- Skywave
- Line-of-Sight (LOS)

Big λ

↓

Small λ

Beyond Line of Sight (BLOS)

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

[1]: SWIC 2024 – STCE, RNLAF & KNMI

Radio bands

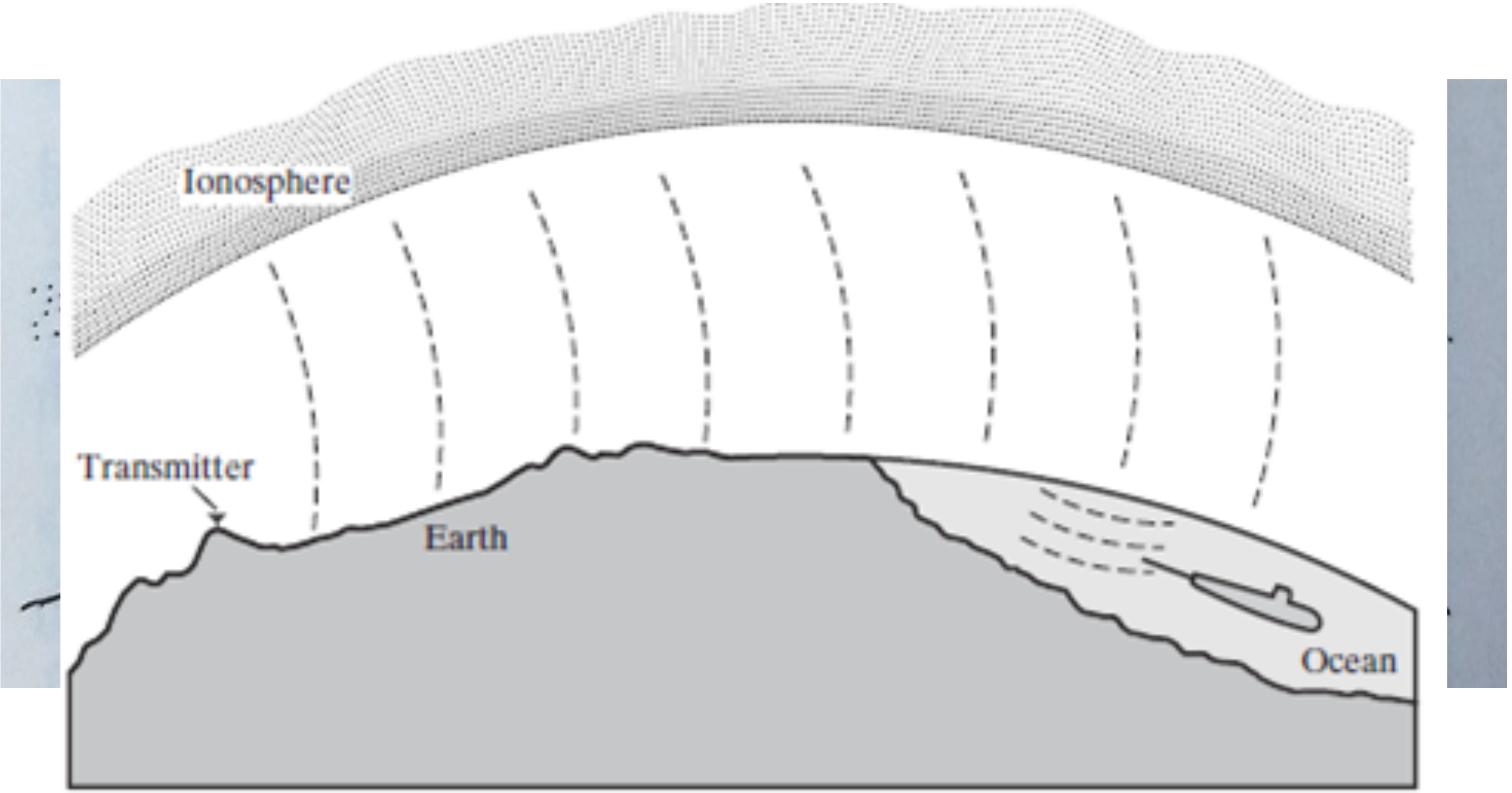
Band Number (ITU)	Abbreviation	Frequency Range	Wavelength Range
1 – 3	ELF	<3	
4	VLF		
5	LF		
6	MF		
7	HF		
8	VHF		
9	UHF		
10	SHF	3	
11	EHF	3	

[1]: SWIC 2024 – STCE, RNLAF & KNMI

DEFENSIE
LA DÉFENSE

ELF - VLF

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

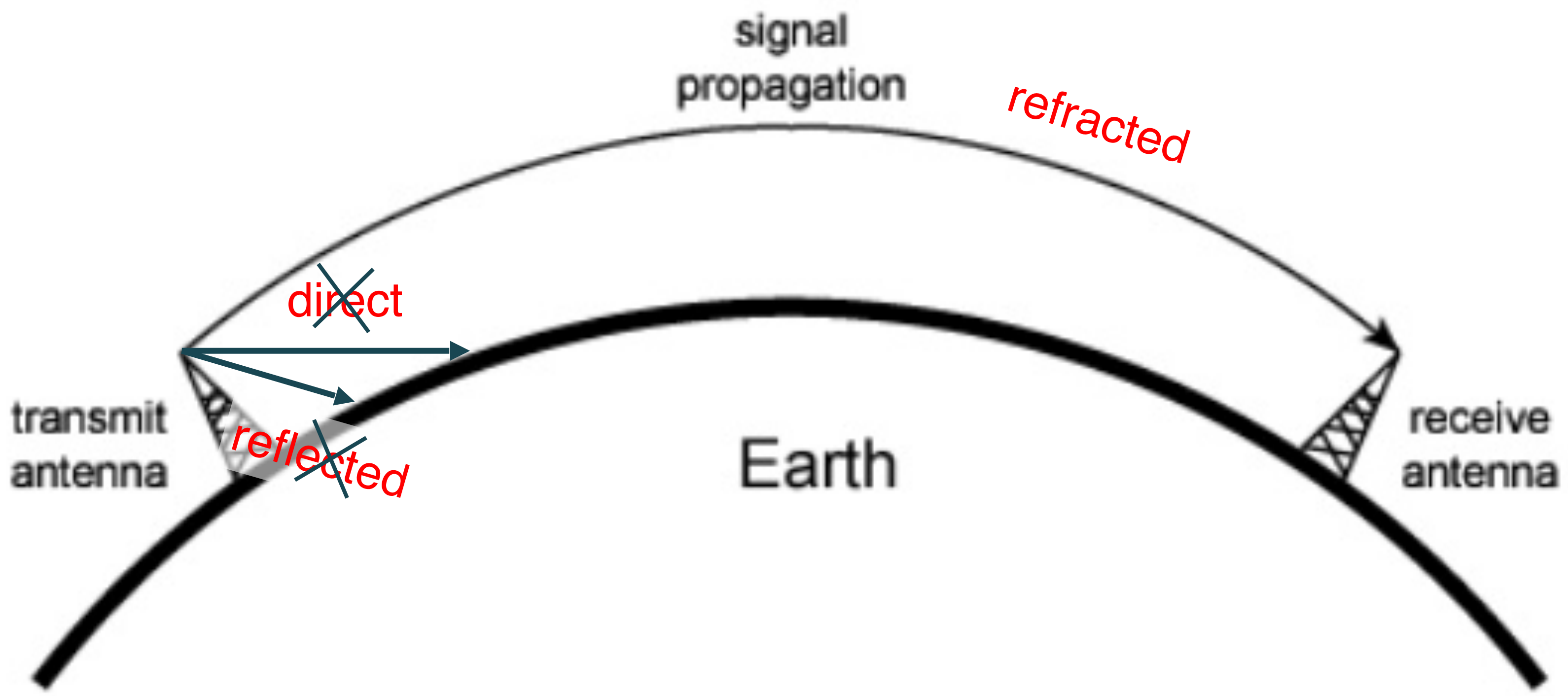


The denser the D layer ionization, the better the propagation

→ Impact of SWx!

[1]: SWIC 2024 – STCE, RNLAF & KNMI

ELF/VLF/LF/MF: Groundwave propagation (3 kHz < f < 3 MHz)



[1]: SWIC 2024 – STCE, RNLAF & KNMI

Groundwave

Higher frequency

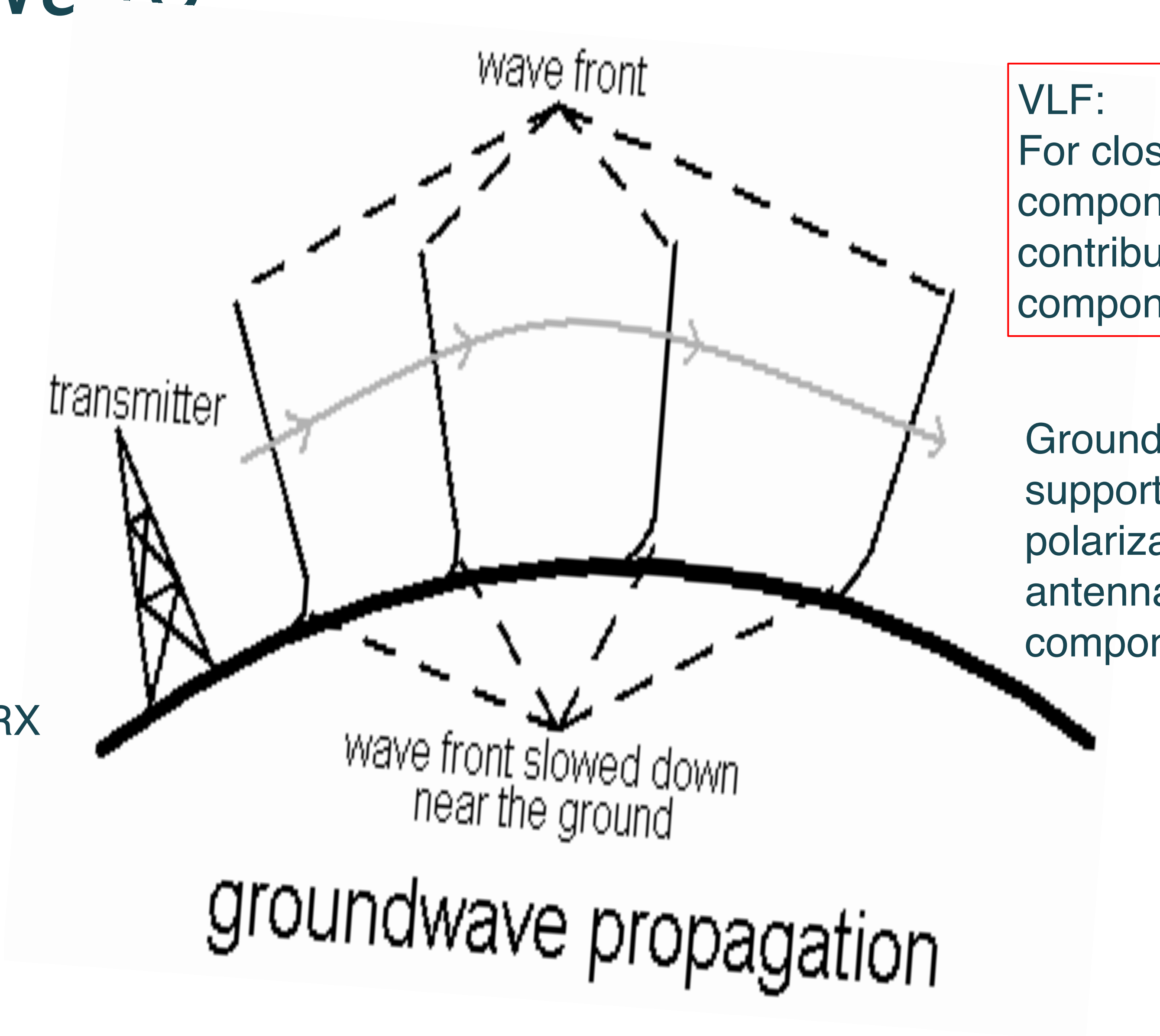
⇓

More ground wave attenuation

More TX power

⇓

More power arriving at RX



VLF:
For close by, the ground wave component is dominant over the contribution of the waveguide component

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

[1]: SWIC 2024 – STCE, RNLAF & KNMI

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

ELF - VLF

Used in:

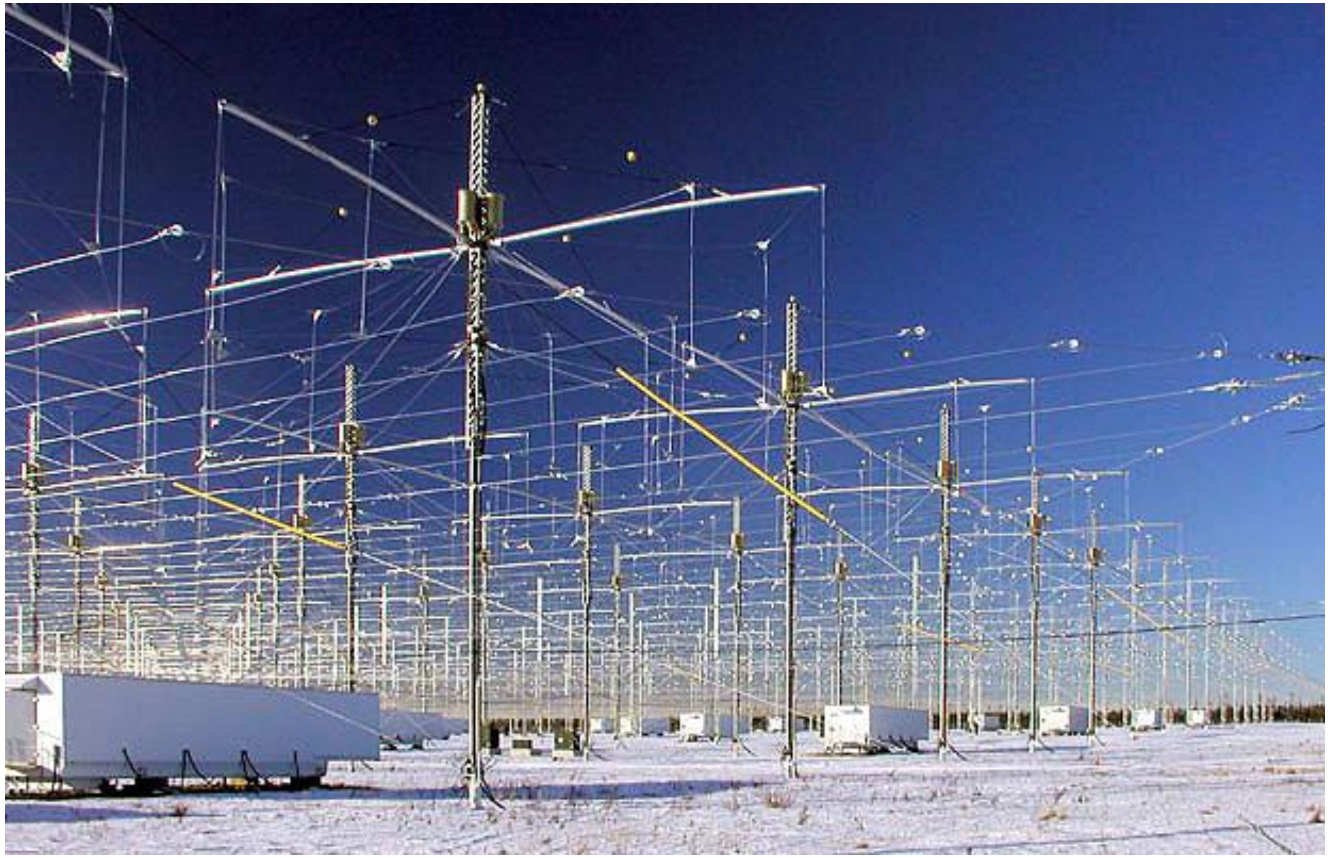
- Radio navigation
- Time beacons
- Secure military communications (submarine)

Propagation mechanism:

1. Excellent ground wave propagation, though attenuation becomes apparent at long distance.
2. Since earth and the D layer together act as a waveguide for these frequencies, the waveguide mechanism is dominant at long range. The stronger the D layer ionization, the better the propagation.

DEFENSIE
LA DÉFENSE

ELF antenna



Huge size (15 – 60 km)
Practically impossible to realize an efficient antenna:
Multi megawatt TX powers are required

[1]: SWIC 2024 – STCE, RNLAF & KNMI

VLF/LF & MF antennas

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

DEFENSIE
LA DÉFENSE

HF

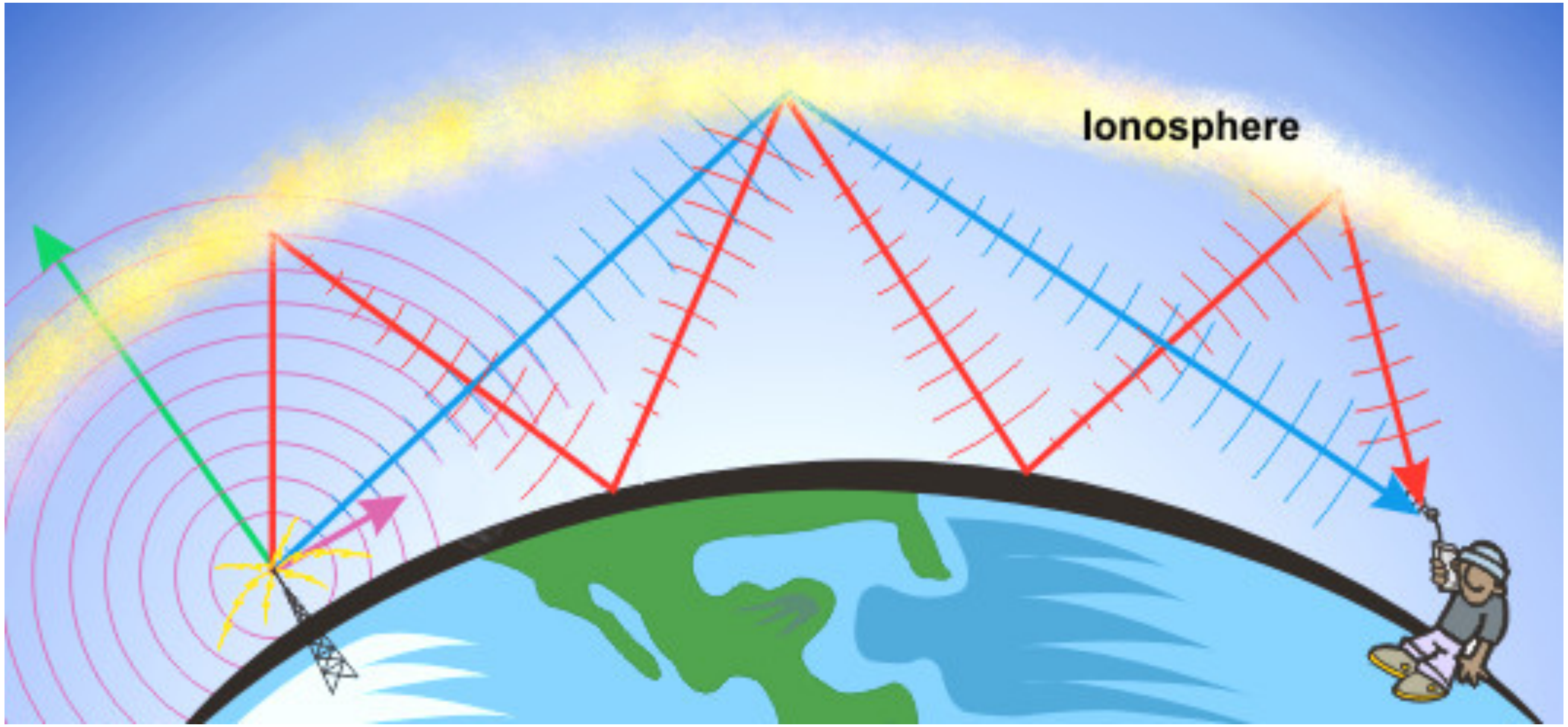
HF: mechanisms

HF propagation mechanisms

- Reflection against the ionosphere (skywave)
- Groundwave
- Line of sight

DEFENSIE
LA DÉFENSE

MF/HF: Skywave propagation



[1]: SWIC 2024 – STCE, RNLAF & KNMI

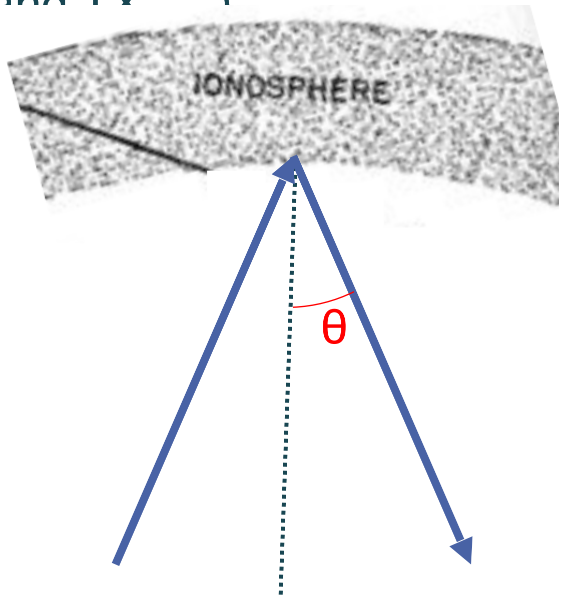
DEFENSIE
LA DÉFENSE

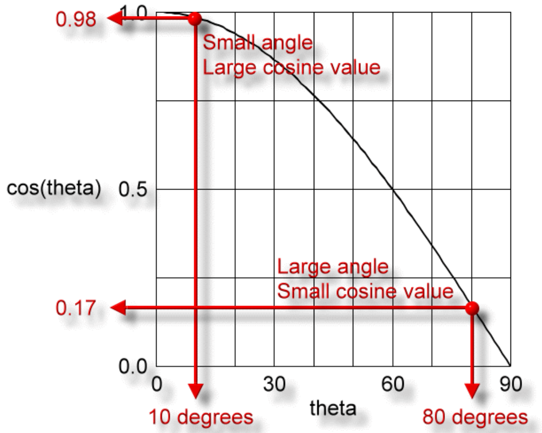
Parameters of ionospheric layers

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 …)

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





E. A. Zobel, "Inclined plane I Zona Land Education," Zona Land Education, [Online]. Available: http://zonalandeducation.com/mstm/physics/mechanics/forces/inclinedPlane/angleAndComponents/angleAndComponents.html. [Accessed 10 10 2022].

Frequency too high for MUF?
- → Wave 'breaks' through the layer

Optimum frequency for stable transmission: 0,8 x MUF

DEFENSIE
LA DÉFENSE

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

Suggestion: check out Ionosphere and Space Weather I Royal Meteorological Institute and look for the M(3000) parameter to see the parameter evolving throughout time.

DEFENSIE
LA DÉFENSE

Parameters of ionospheric layers

Lowest Useable Frequency
→ Result of the D-layer attenuating every wave passing through
→ Attenuation ~ $1/f^2$
→ 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

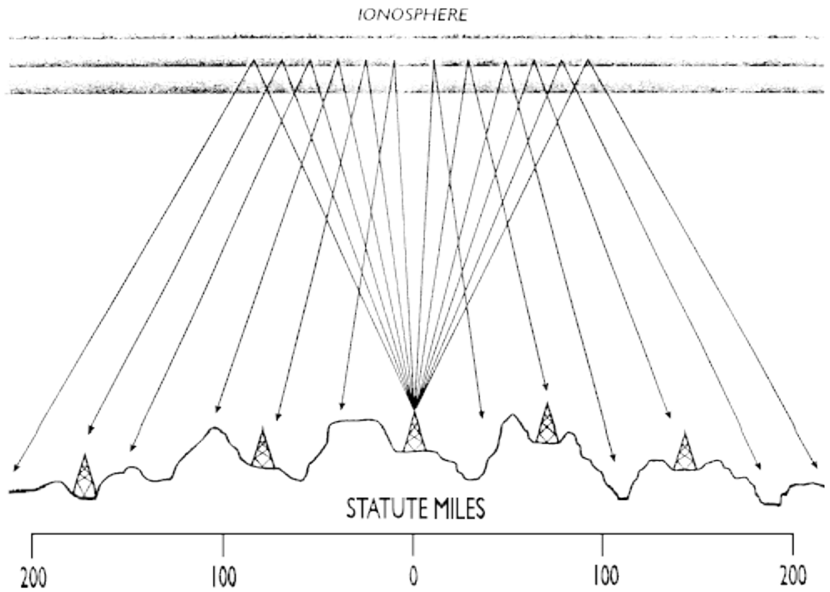
Parameters of ionospheric layers

- **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**

Frequency considerations

Radiating at high angle

Quiz:
Radiating upwards means MUF is:
- close to CUF
- significantly higher than CUF
- significantly lower than CUF



DEFENSIE
LA DÉFENSE

Radiating at high angle

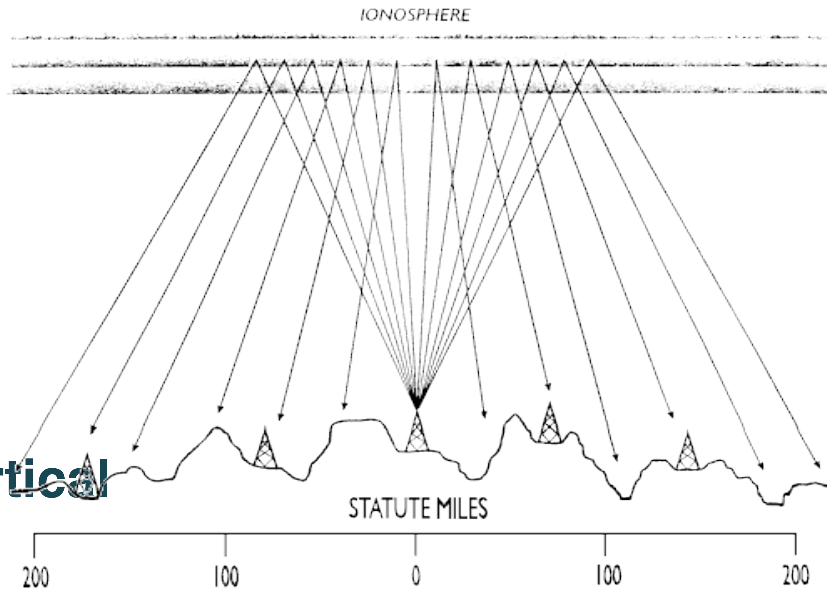
Quiz:
Radiating upwards means **MUF is**:
- close to CUF
~~- significantly higher than CUF~~
~~- significantly lower than CUF~~

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

Scenario:

- Conversation partner is close by (tactical situation)
- Conversation partner is behind obstacles (hills, …)

→ The **incidence** angle of your wave **should be nearly vertical**



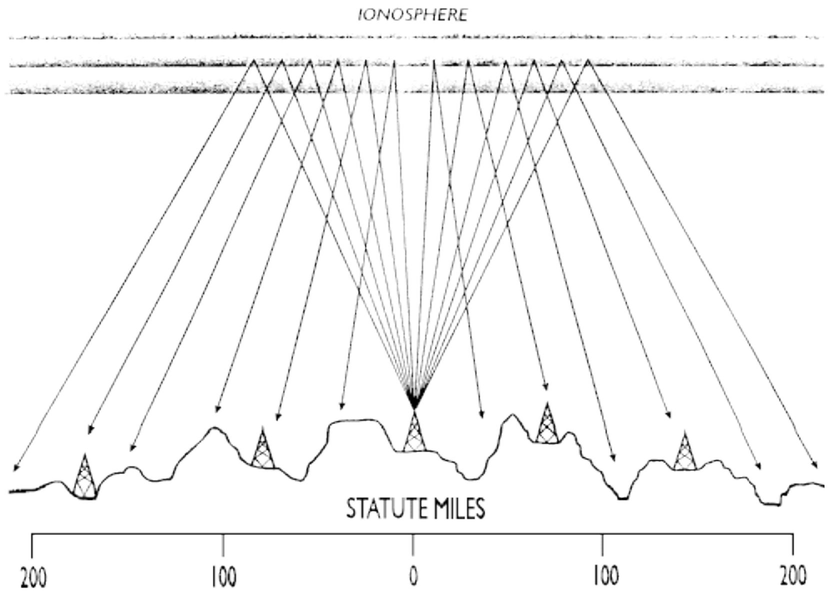
CUF only tells something about the state of the *local* ionosphere.

DEFENSIE
LA DÉFENSE

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).

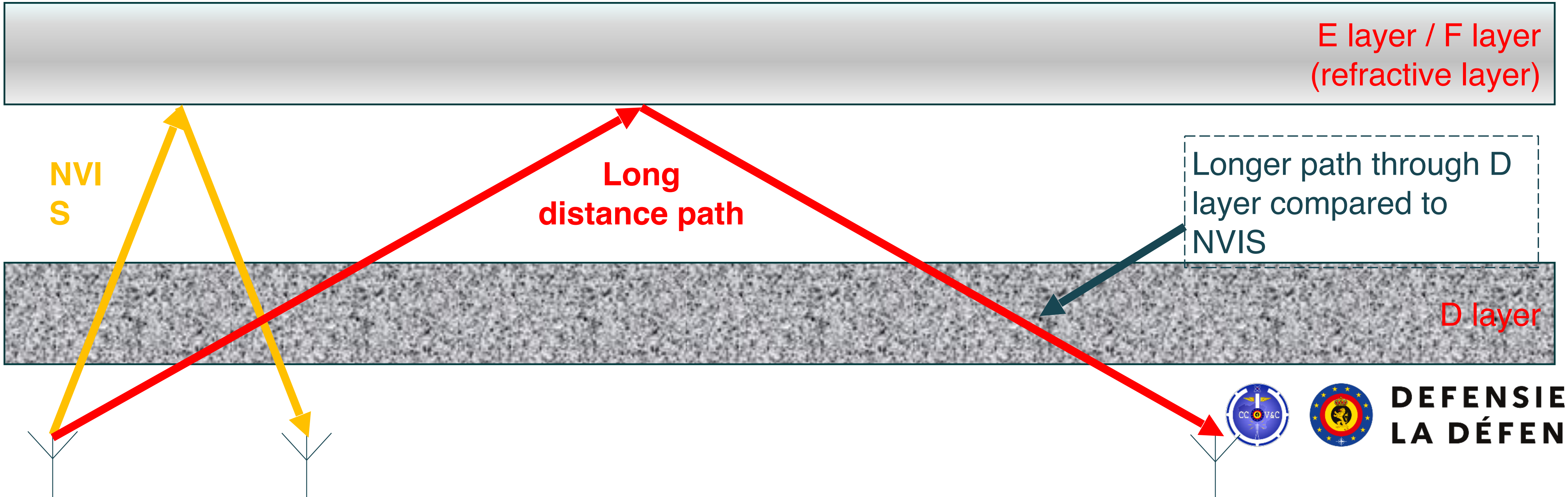


DEFENSIE
LA DÉFENSE

Influence of the D layer on skywave

The D layer attenuates signals proportional with 1/f²

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



Frequency selection

→Low frequency for NVIS scenarios

→Higher frequency for long distance

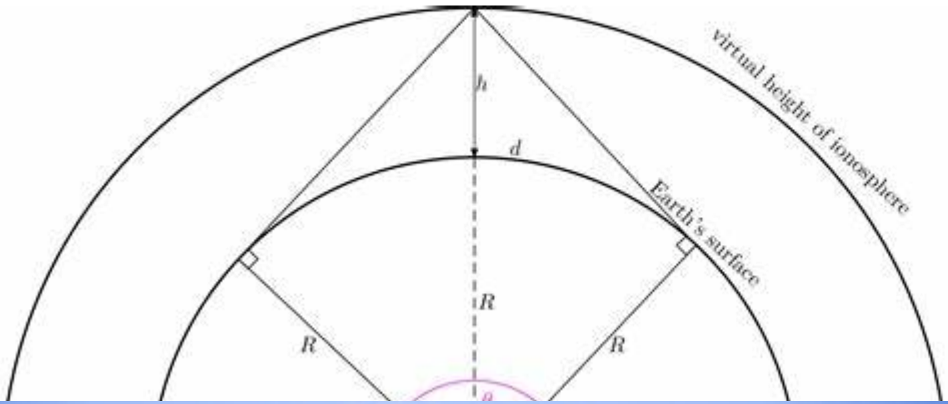
DEFENSIE
LA DÉFENSE

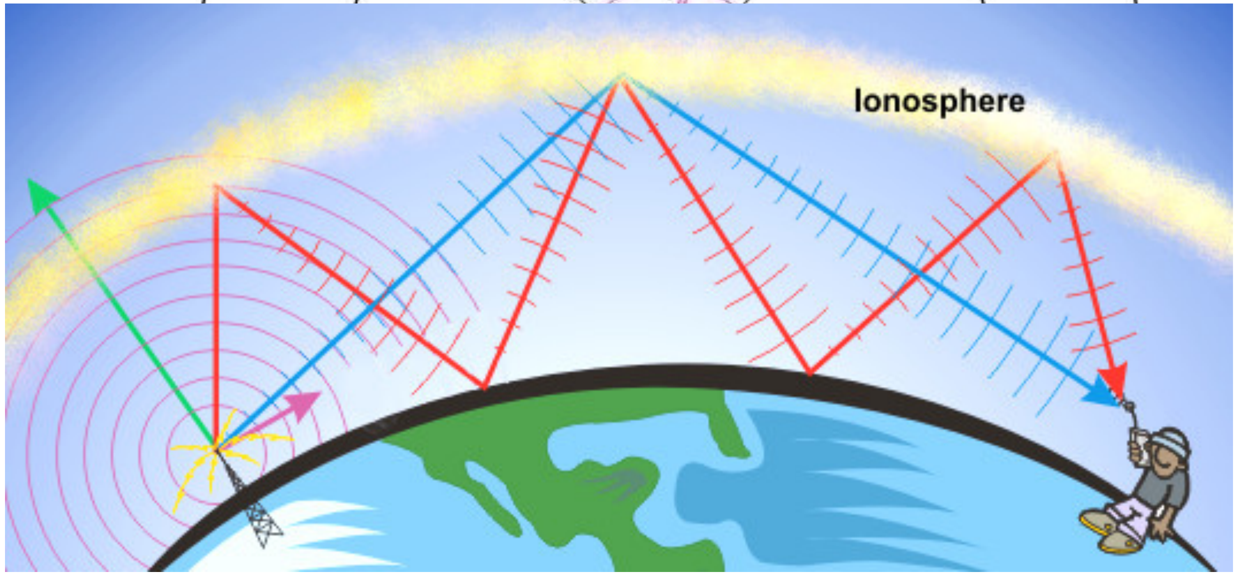
Multiple hops

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.

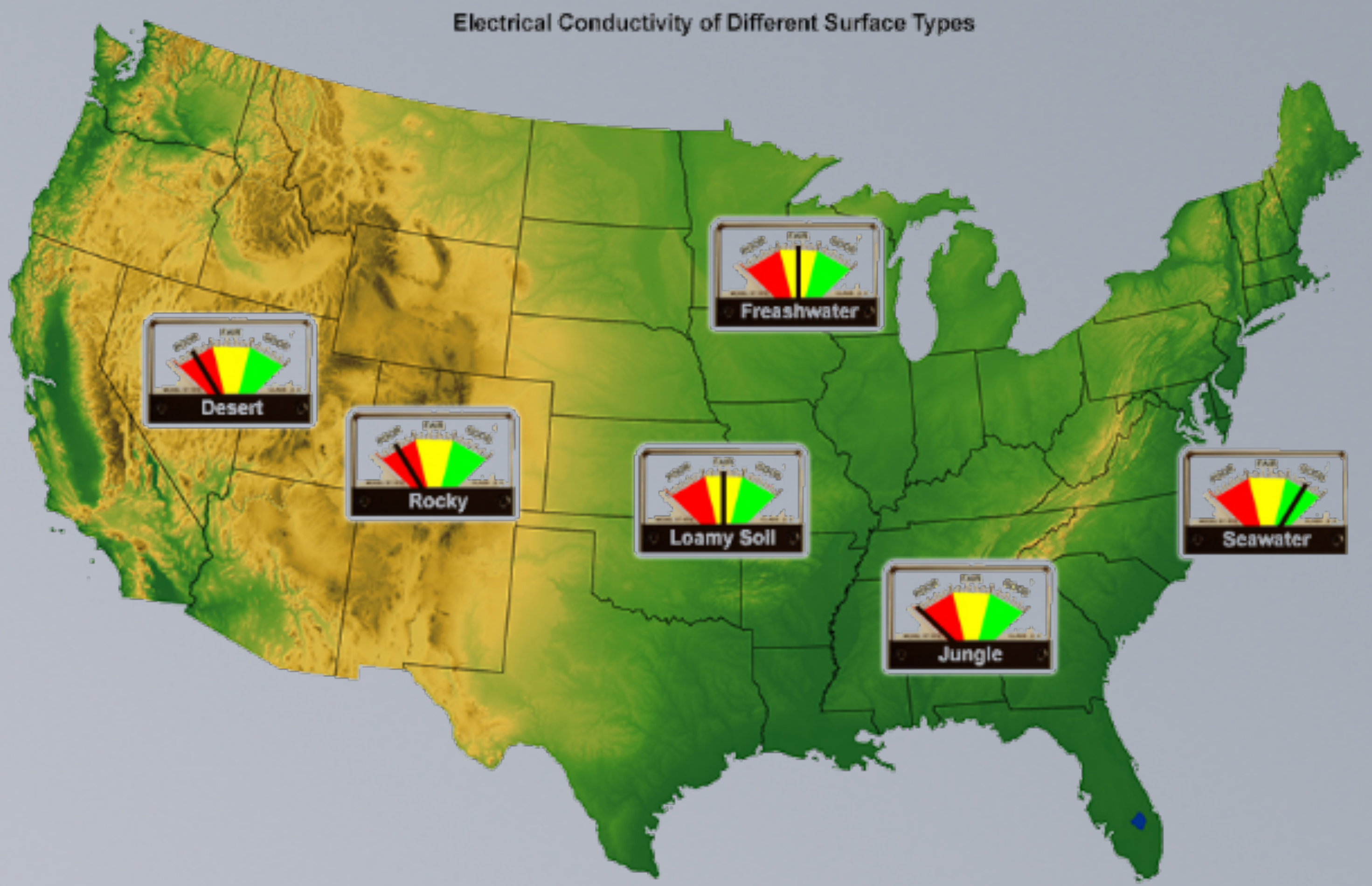




[1]: SWIC 2024 – STCE, RNLAF & KNMI

DEFENSIE
LA DÉFENSE

Multiple hops – soil type



Poor reflectors:
- Rock
- Desert
- Jungle

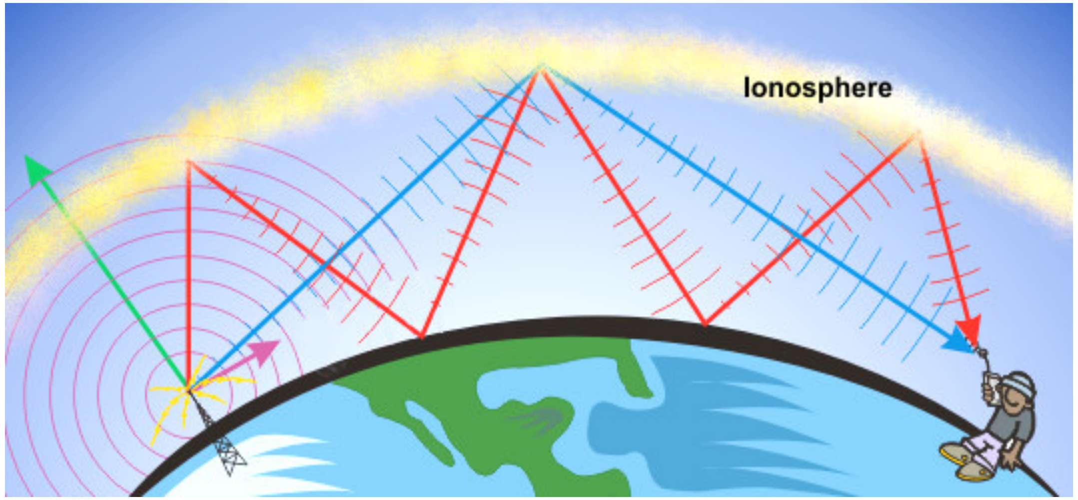
Good reflectors:
- Sea water
- (Freshwater)

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 inexisting frequency window overlaps



[1]: SWIC 2024 – STCE, RNLAF & KNMI

DEFENSIE
LA DÉFENSE

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

Skip zone

Quiz:

Suppose CUF is 3 MHz for the entire region.
You are allocated only use of 4 MHz.

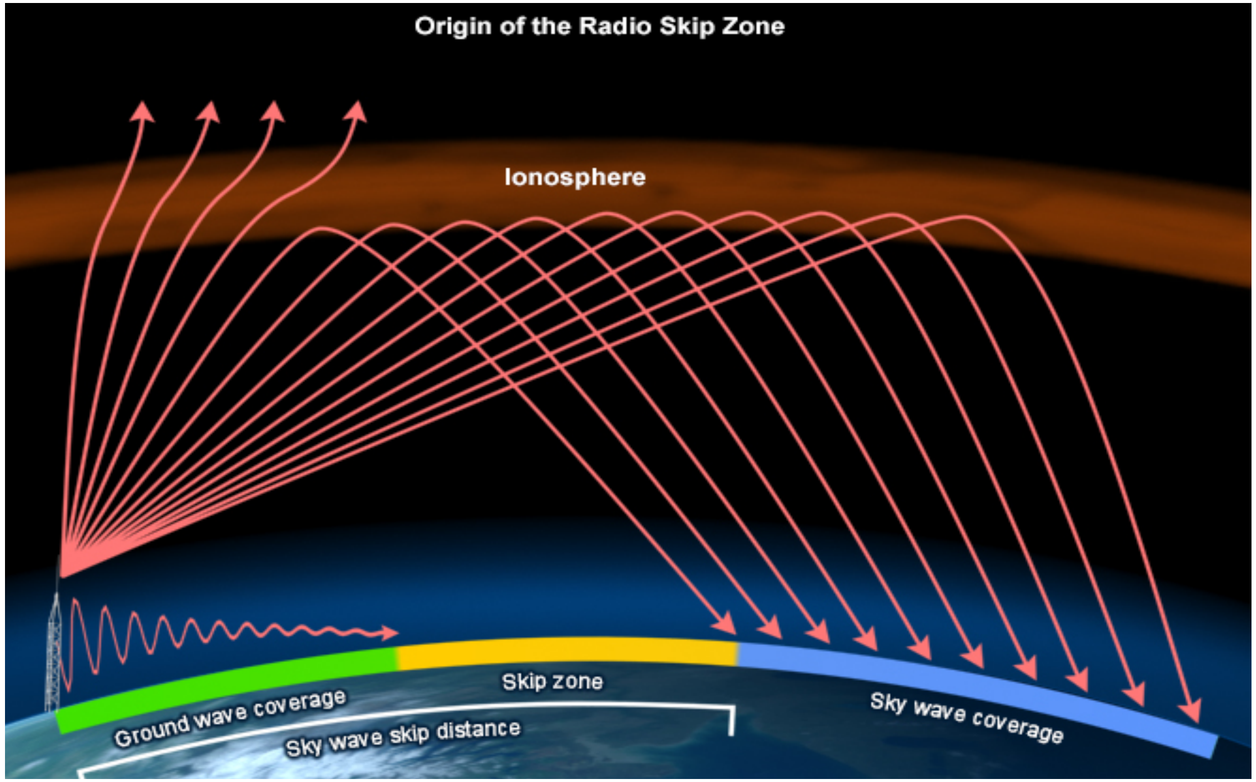
Remember: at 1000 km away, usually the MUF is about 2x the CUF

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!

MUF > CUF? No!

No link!



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

DEFENSIE
LA DÉFENSE

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

DEFENSIE
LA DÉFENSE

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

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)

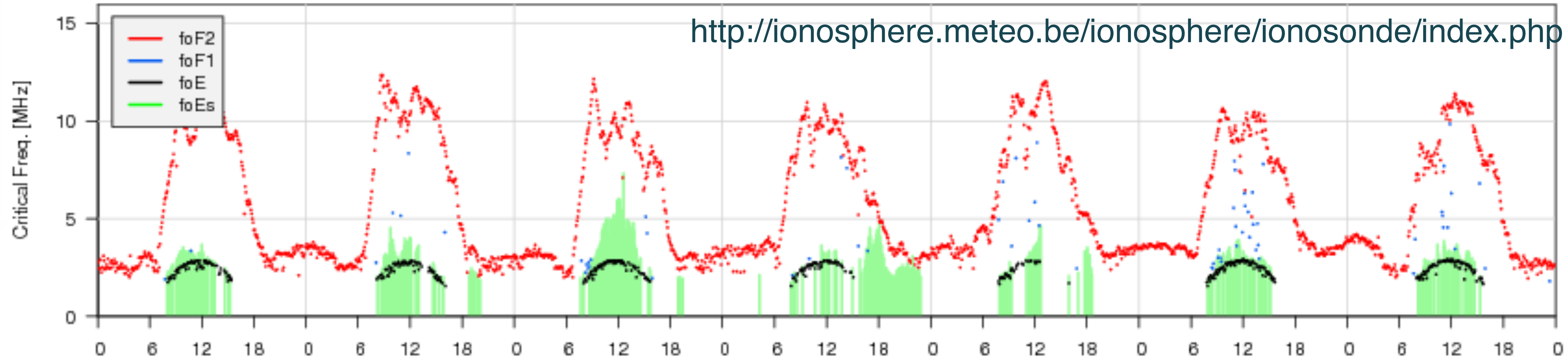
DEFENSIE
LA DÉFENSE

Typical CUF values at medium latitude

Ionisation:

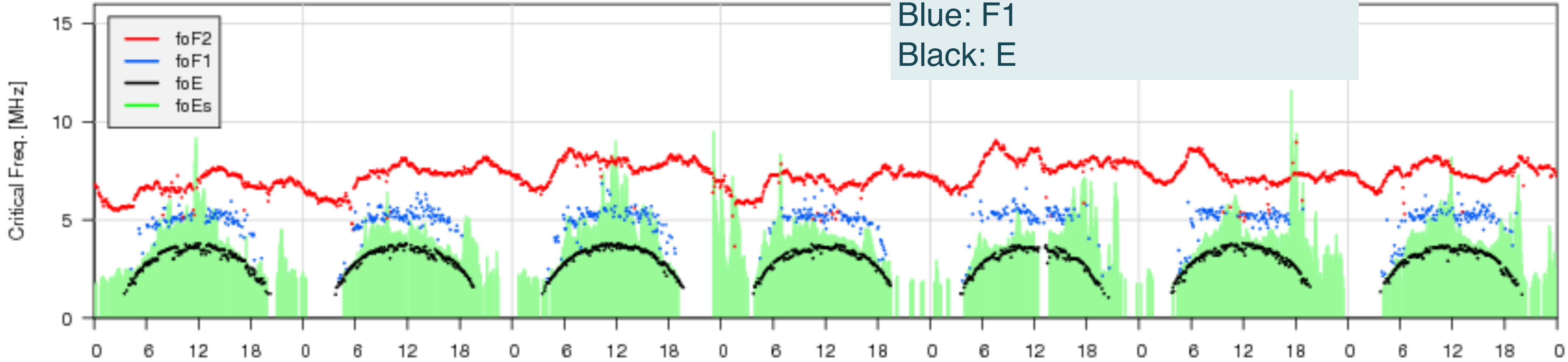
- Day and night is a clear difference (day is obviously more ionized)
- Usually more ionisation (higher MUF) in summer
- More ionisation during solar maximum

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



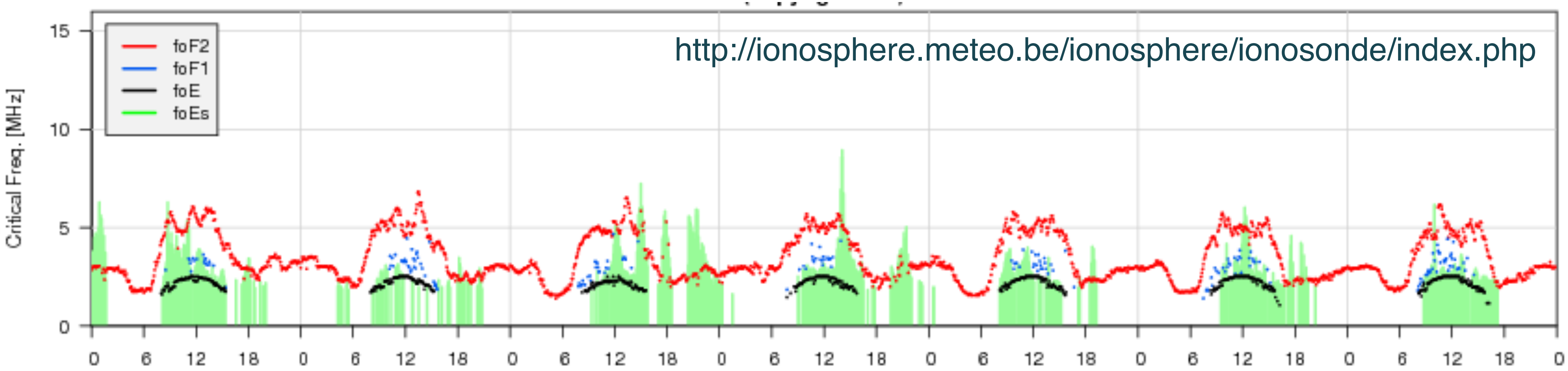
High solar cycle, winter (09-15/01/2025)

Critical frequency of:
Red: F2
Blue: F1
Black: E



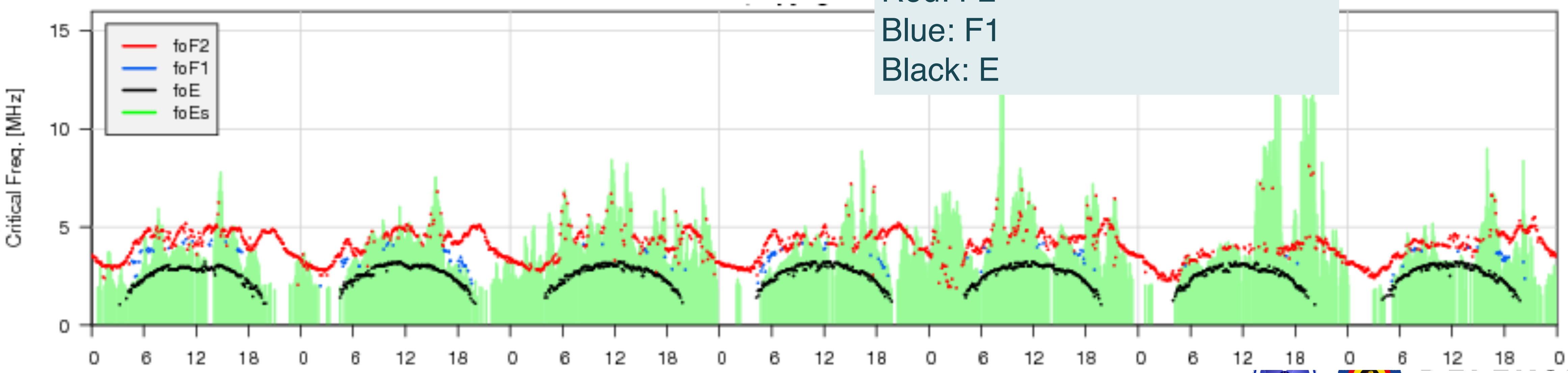
High solar cycle, summer (09-15/07/2024)

Ionosonde at Dourbes (DB049), © RMI



Low solar cycle, winter (09-15/01/2020)

Critical frequency of:
Red: F2
Blue: F1
Black: E



Low solar cycle, summer (09-15/07/2020)

LA DÉFENSE

Ionosonde at Dourbes (DB049), © RMI

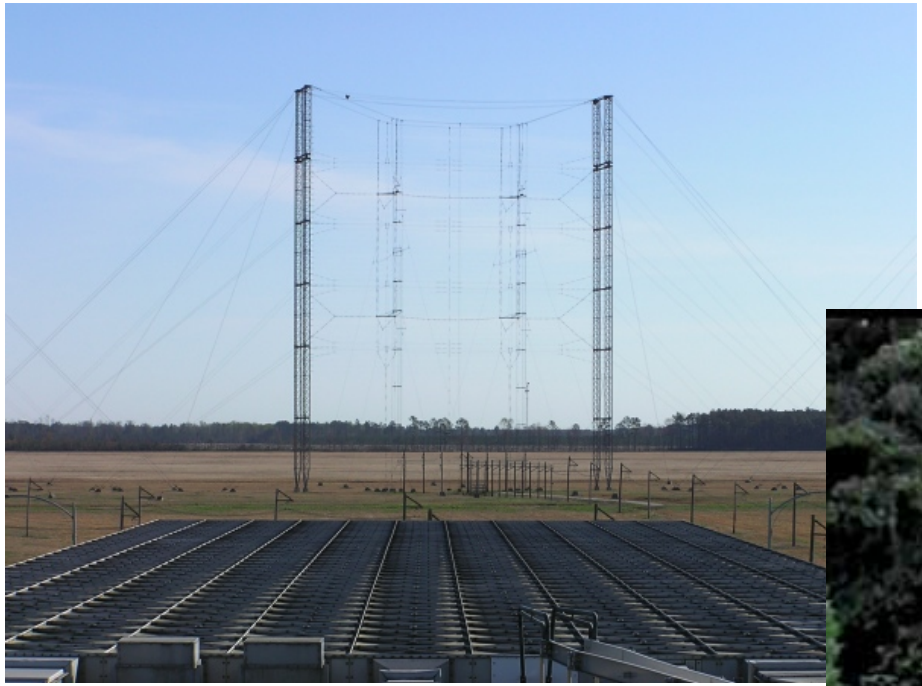
Why not always prefer low frequencies?

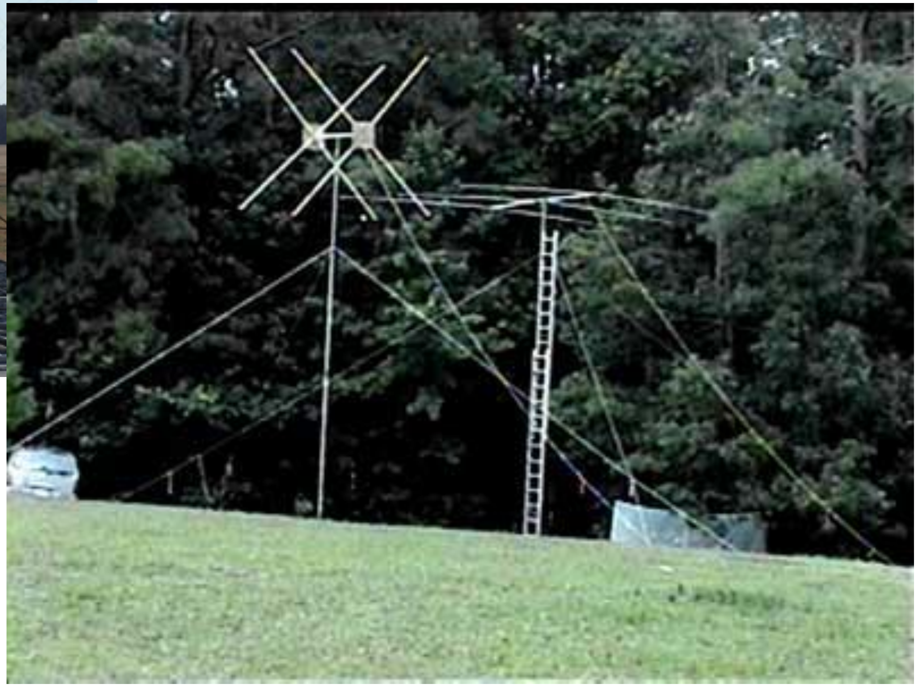
- Frequency availability

- 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

DEFENSIE
LA DÉFENSE

HF antennas





[1]: SWIC 2024 – STCE, RNLAF & KNMI

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

The radio path

Note that 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.

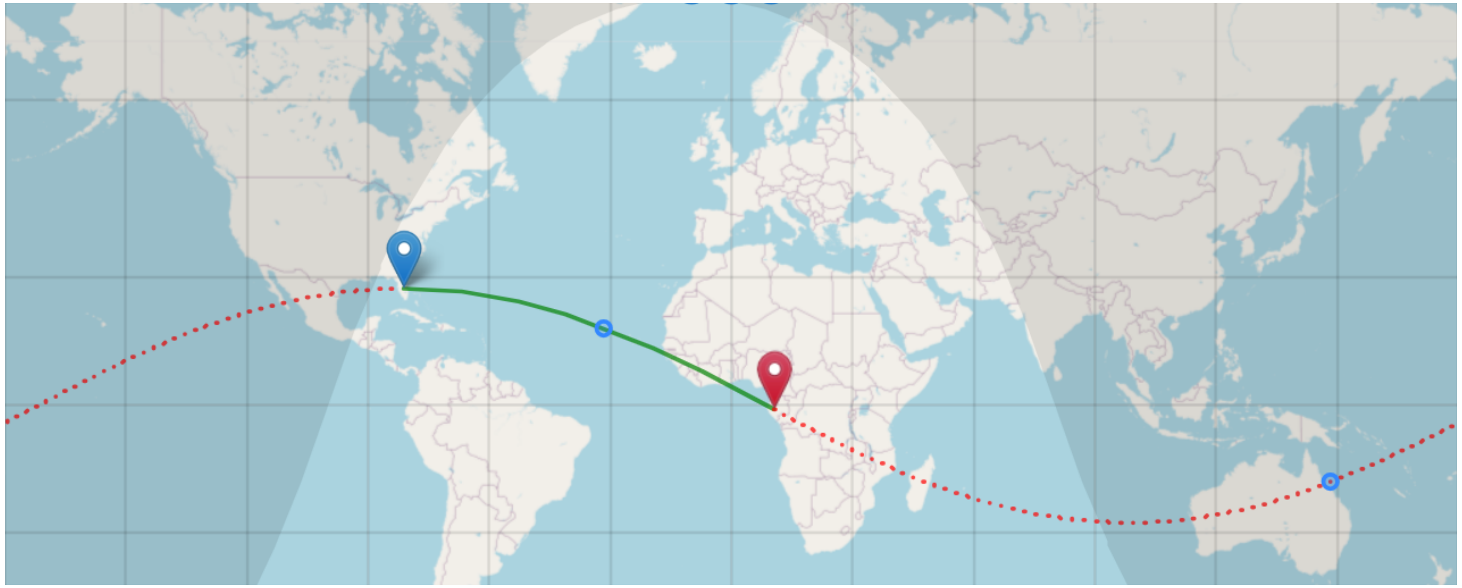
Note that the HF signal is reached in an immense area!
→ Your adversary will probably hear you too
→ Tactical cells of multiple 100’s of kms

→ 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/

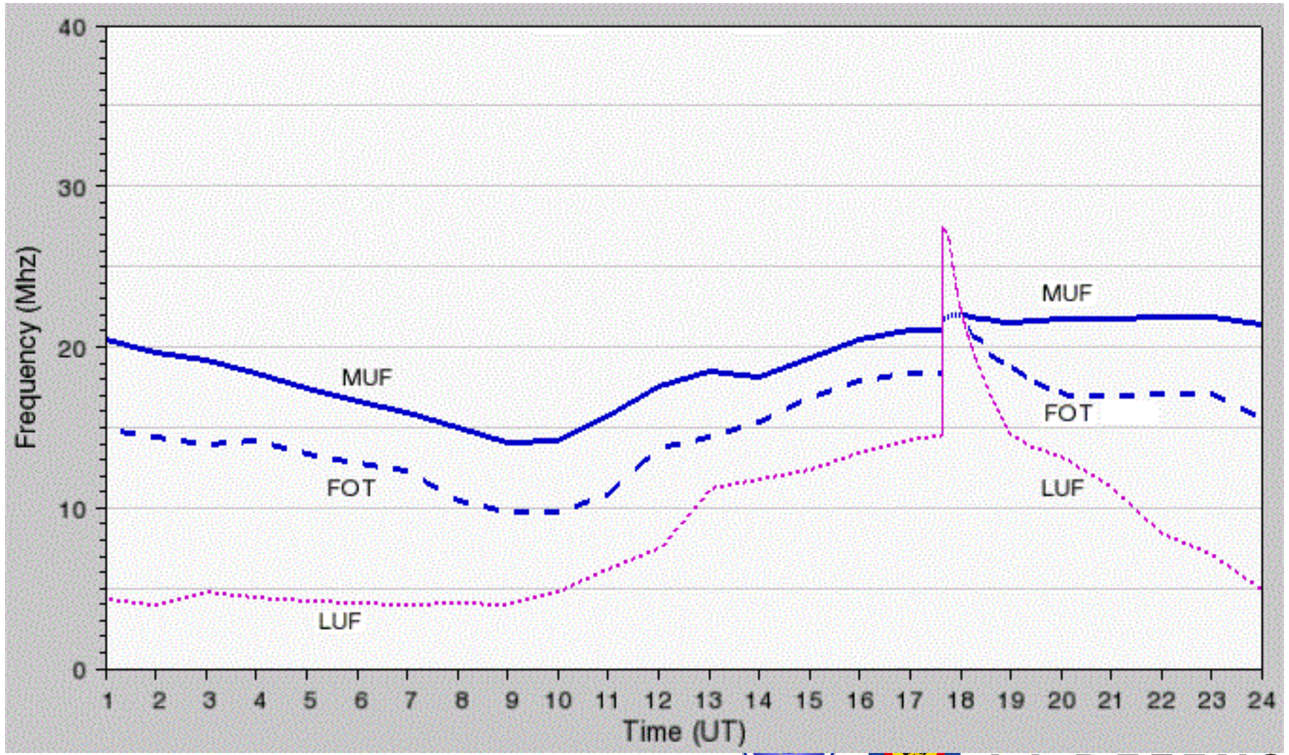
DEFENSIE
LA DÉFENSE

Short Wave Fade

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



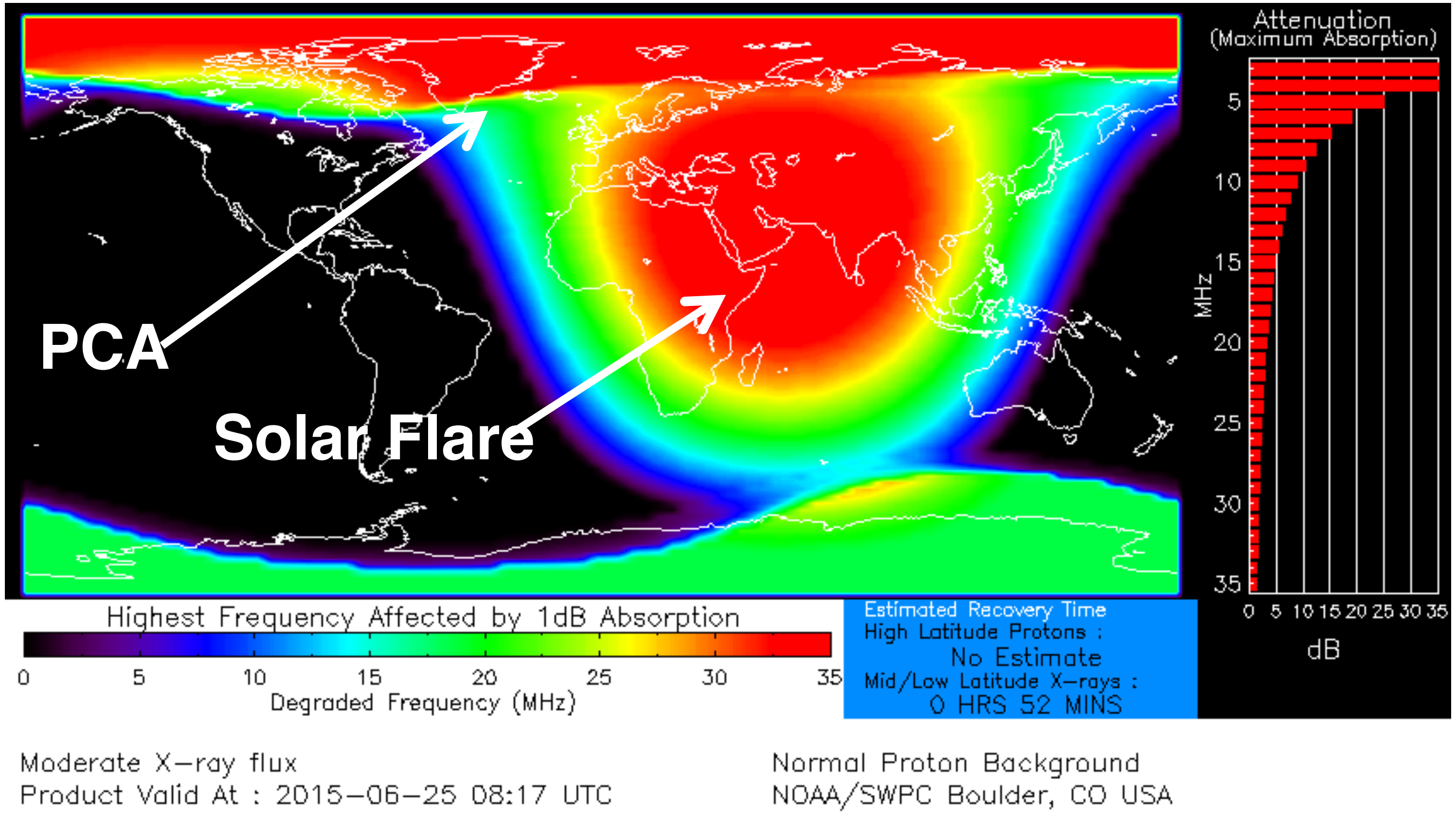
[1]: SWIC 2024 – STCE, RNLAF & KNMI

LA DEFENSE

Short Wave Fade

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

Polar Cap Absorption may even last up to 10 days



[1]: SWIC 2024 – STCE, RNLAF & KNMI

DEFENSIE
LA DÉFENSE

Polar Cap Absorption

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

[2] Australian Space Weather Forecasting Centre

DEFENSIE
LA DÉFENSE

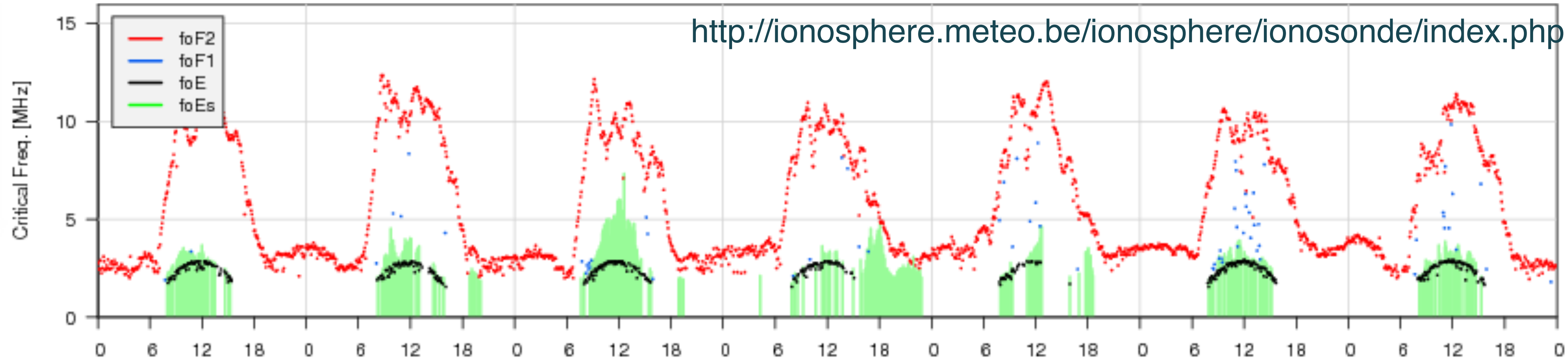
E layer propagation

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.

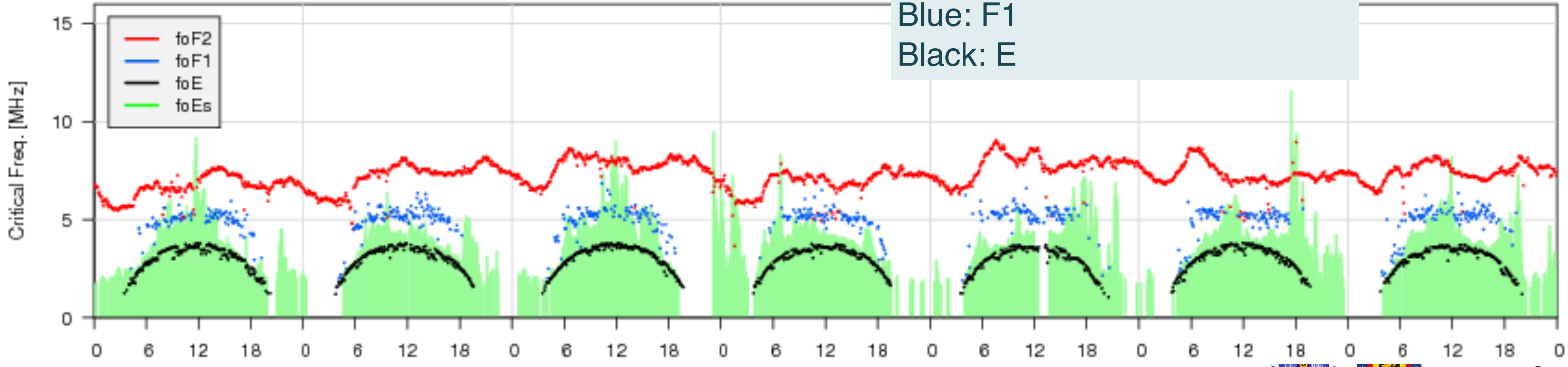
The E layer disappears at night.

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



High solar cycle, winter (09-15/01/2025)

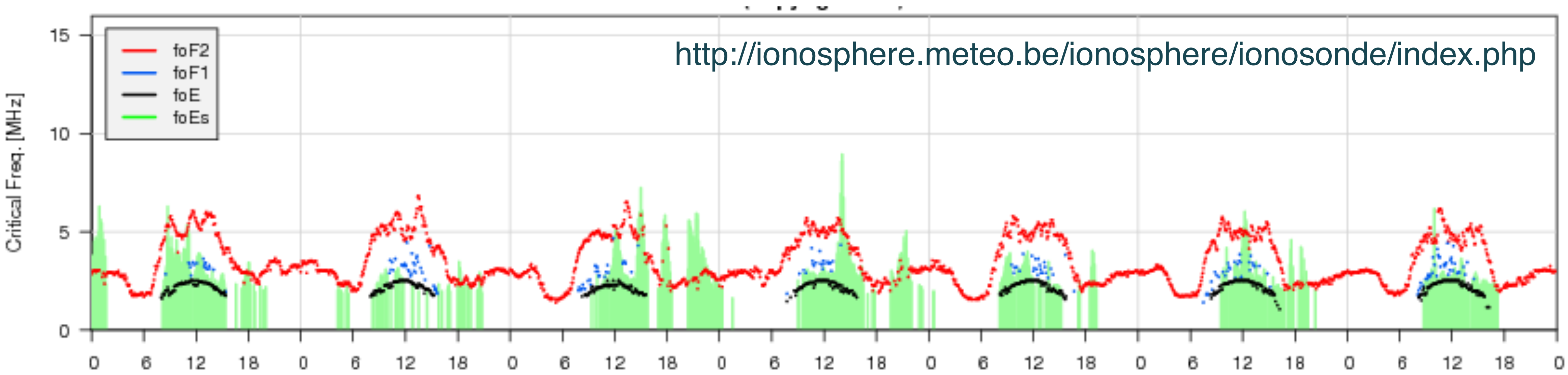
Critical frequency of:
Red: F2
Blue: F1
Black: E



High solar cycle, summer (09-15/07/2024)

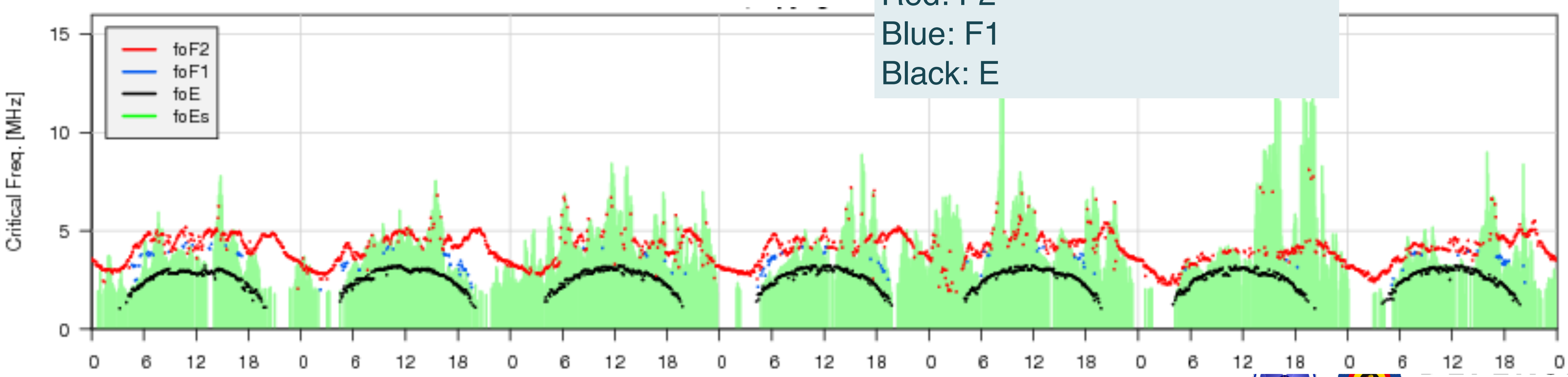
SIE
LA DÉFENSE

Ionosonde at Dourbes (DB049), © RMI



Low solar cycle, winter (09-15/01/2020)

Critical frequency of:
Red: F2
Blue: F1
Black: E



Low solar cycle, summer (09-15/07/2020)

LA DÉFENSE

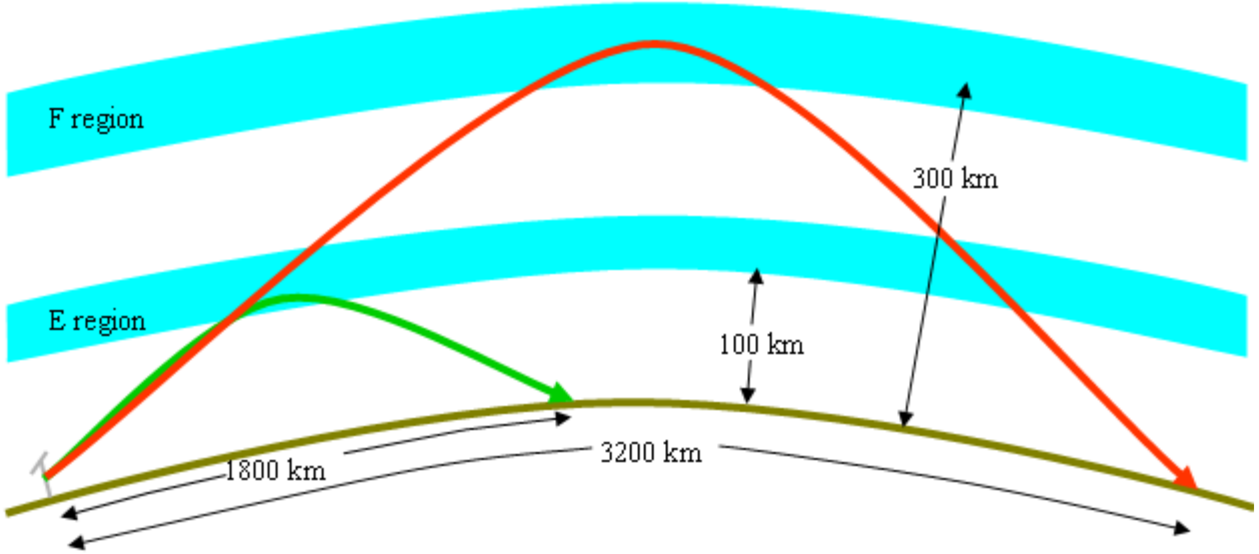
Ionosonde at Dourbes (DB049), © RMI

E layer propagation

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

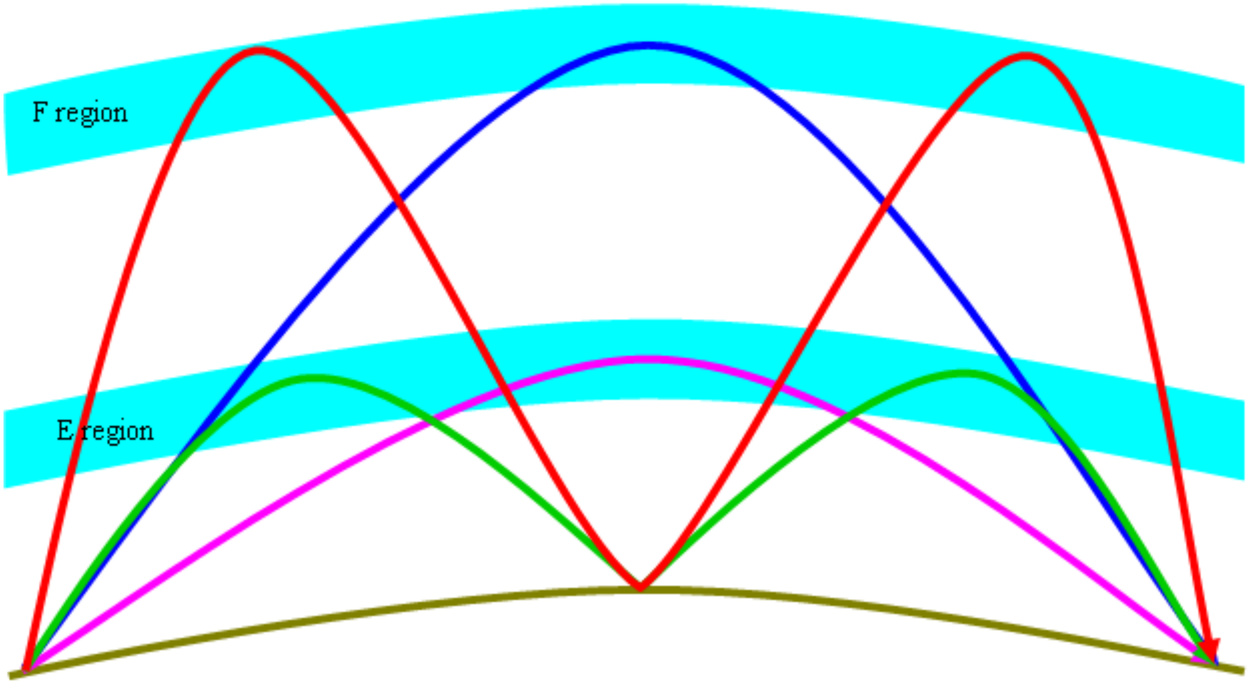


[2] Australian Space Weather Forecasting Centre

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.

[2] Australian Space Weather Forecasting Centre

DEFENSIE
LA DÉFENSE

DEFENSIE
LA DÉFENSE

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 an interplay of different physical phenomena
    - Volcanic eruptions
    - Rocket launches
    - …

DEFENSIE
LA DÉFENSE

Sporadic E

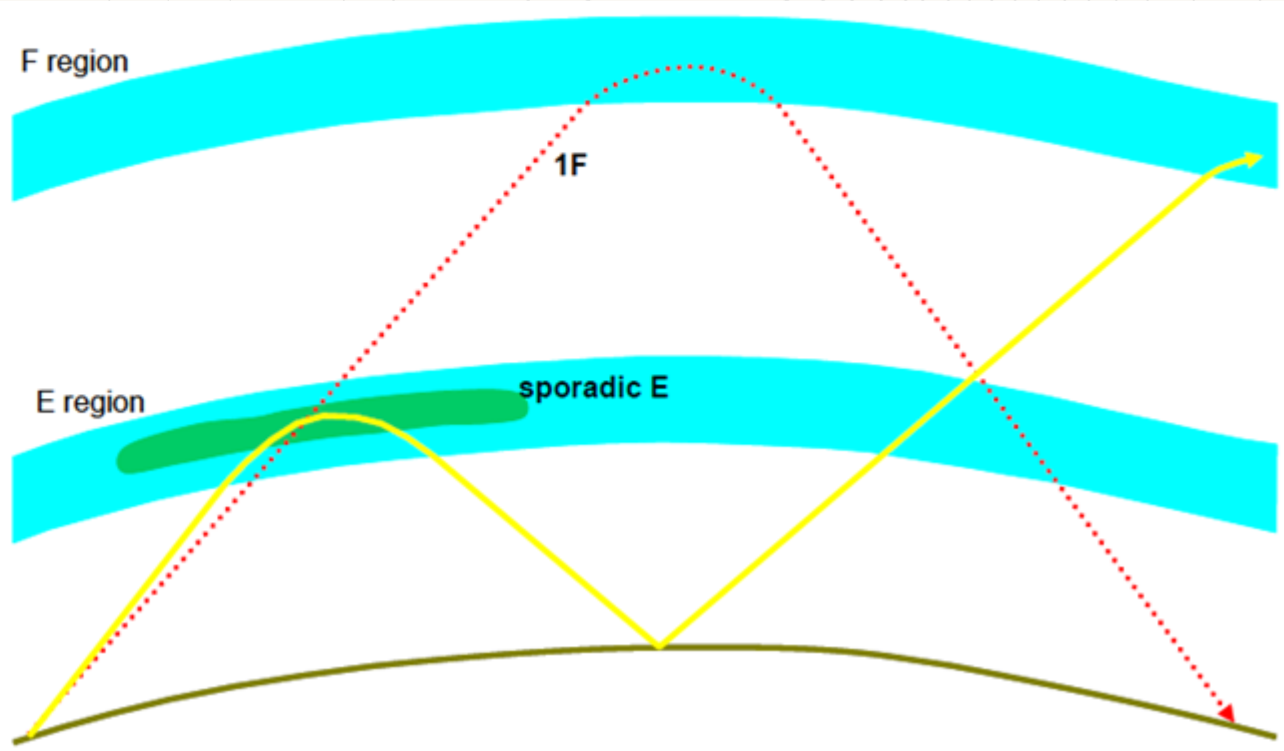
Abbreviated as Es

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



[2] Australian Space Weather Forecasting Centre

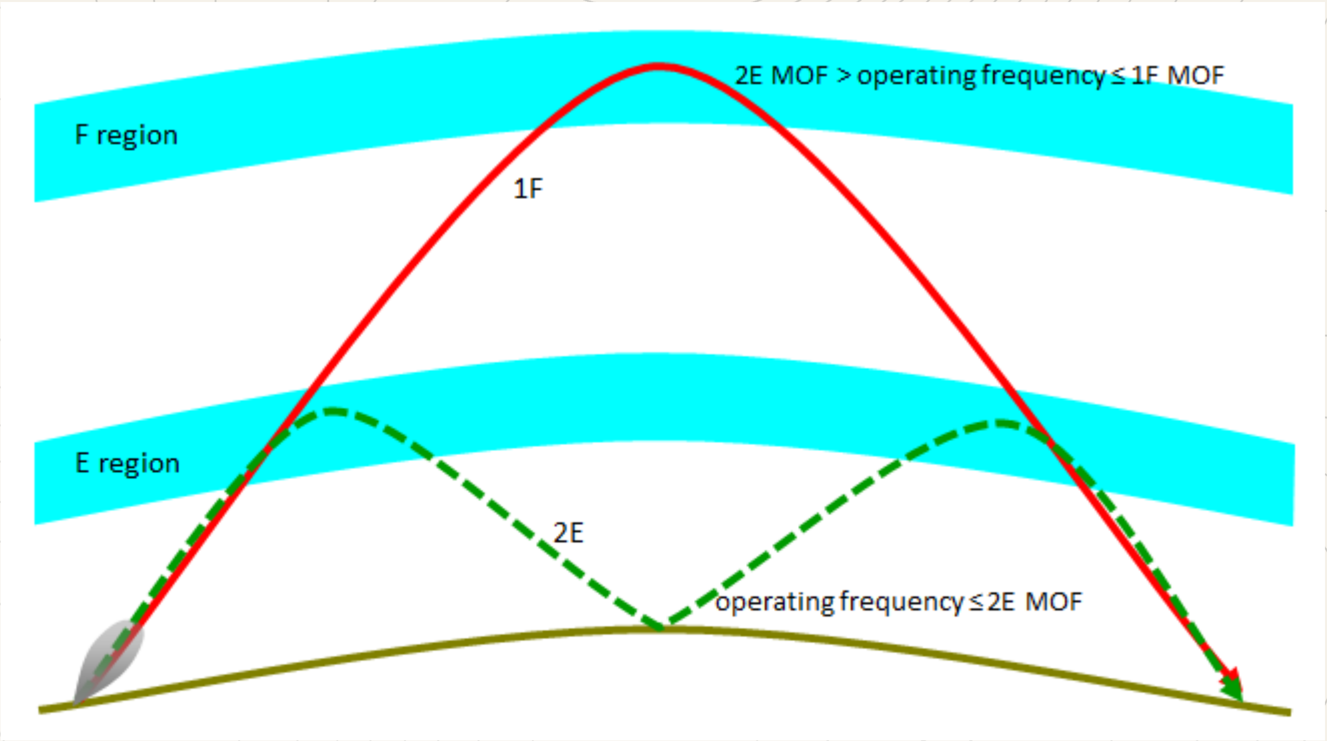
DEFENSIE
LA DÉFENSE

Sporadic E: blanketing

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

Ionograms show blanketing:
Nothing reflects against the F layer

- Reflection only against Es if MUF(Es) > freq
- No reflection, wave towards space if MUF(F) < freq > MUF(Es)



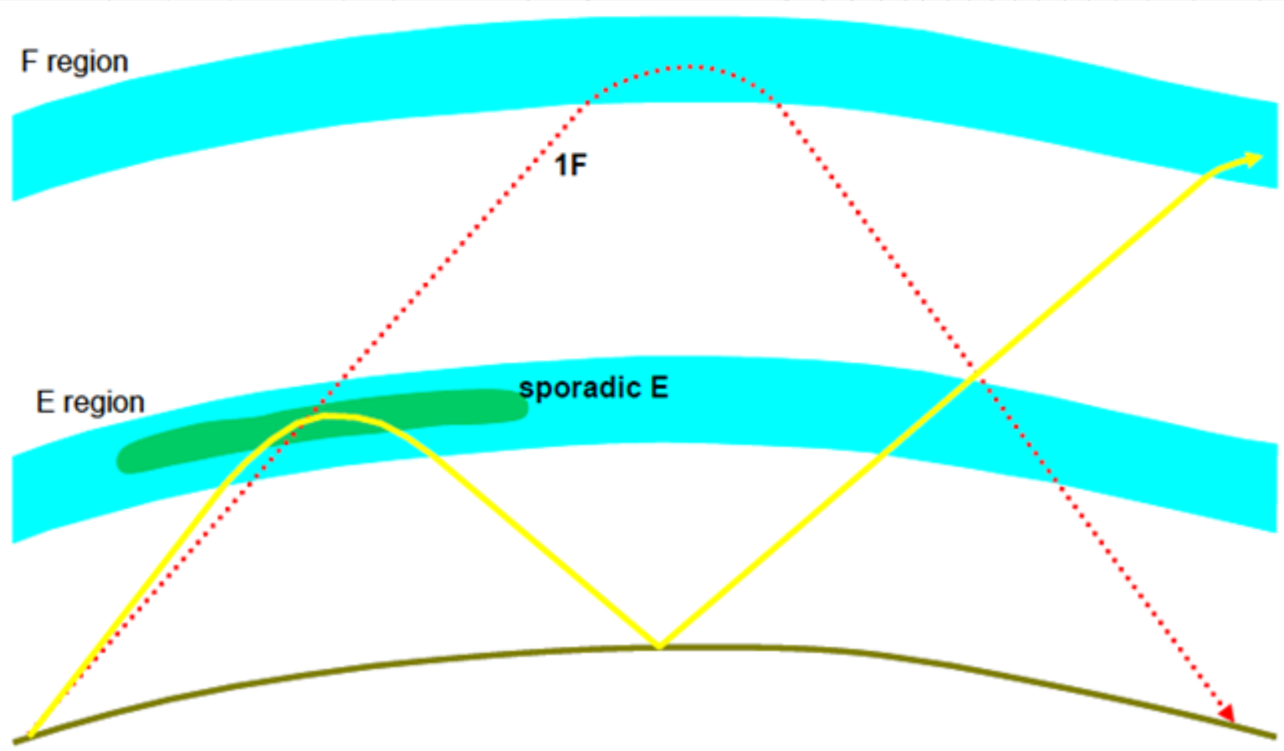
[2] Australian Space Weather Forecasting Centre

DEFENSIE
LA DÉFENSE

Sporadic E

Ionization can be extreme: even reflecting 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

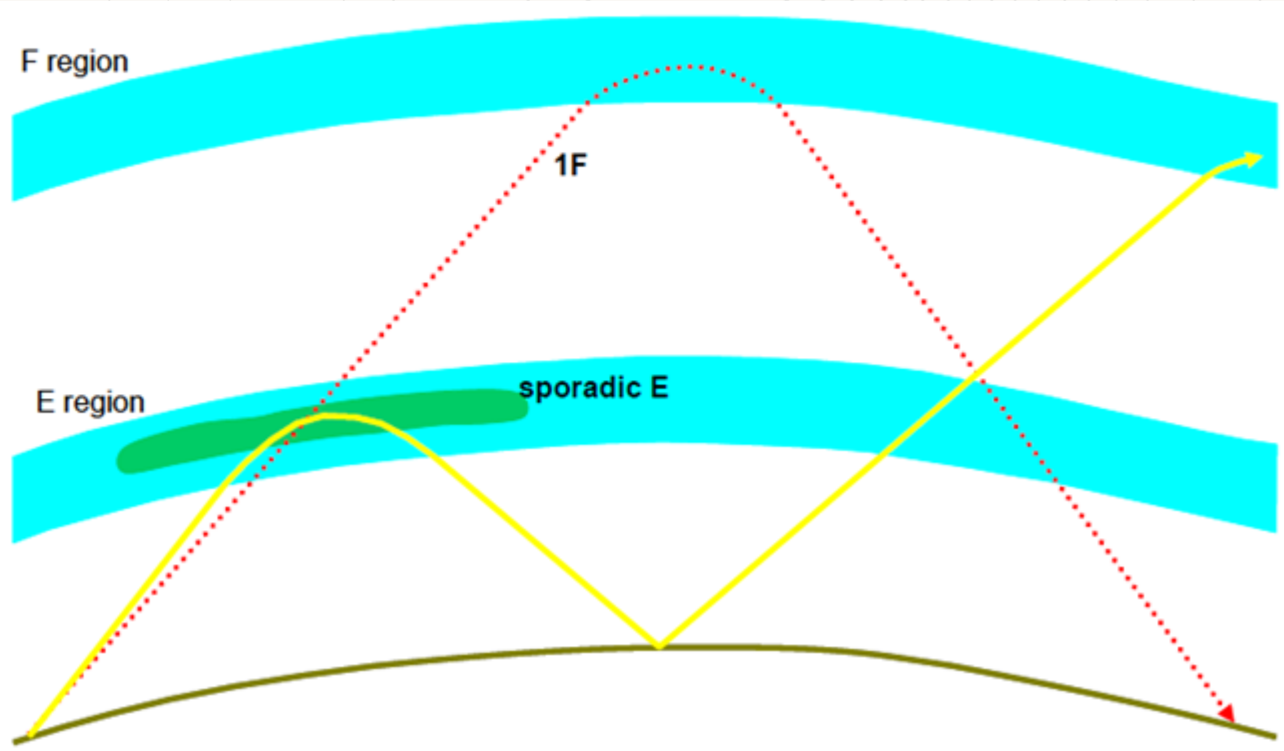


[2] Australian Space Weather Forecasting Centre

DEFENSIE
LA DÉFENSE

Sporadic E

More hops increase signal attenuation:
- More bounces against the ground
- More passes through D layer

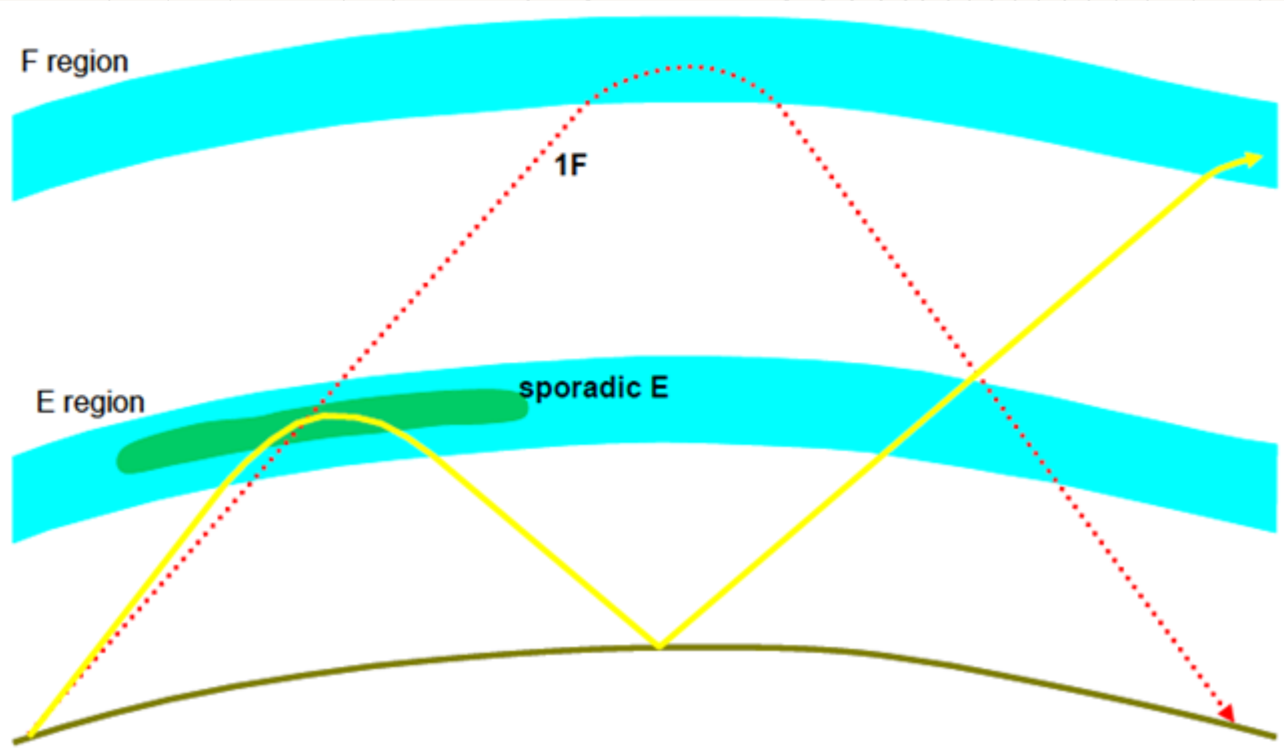


[2] Australian Space Weather Forecasting Centre

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)



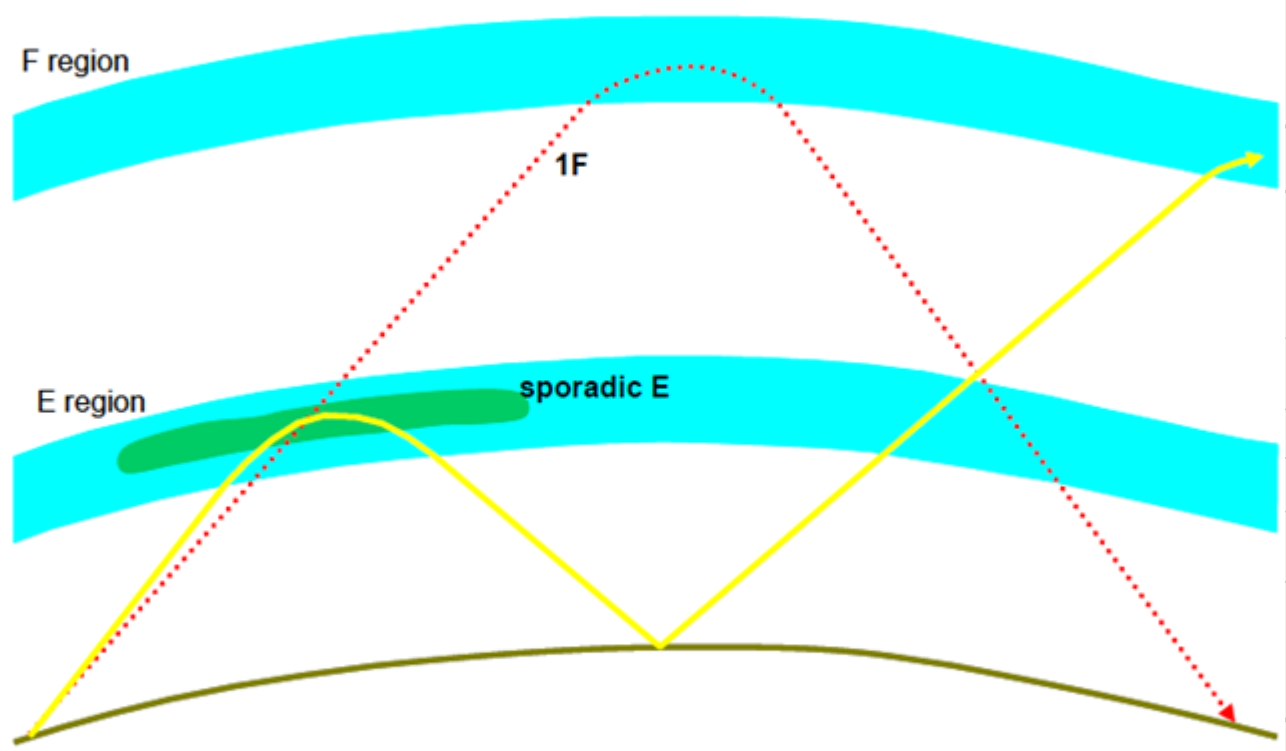
[2] Australian Space Weather Forecasting Centre

DEFENSIE
LA DÉFENSE

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

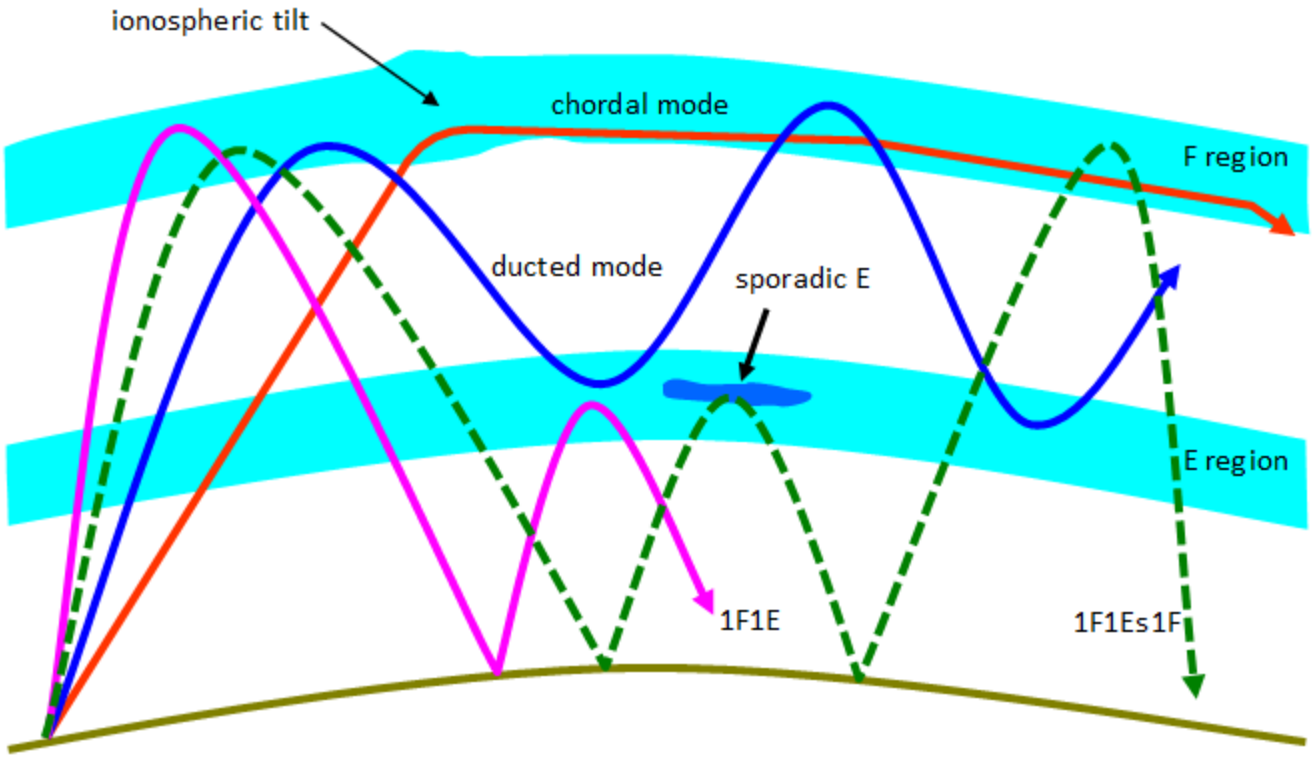


[2] Australian Space Weather Forecasting Centre

Chordal mode

Chordal mode:
An 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 passages ground reflections…)
→ Only comes down at another irregulari (hence completely coincidental)
→ Superb signal quality over extreme distances (up to worldwide) since very little power was lost



[2] Australian Space Weather Forecasting Centre

DEFENSIE
LA DÉFENSE

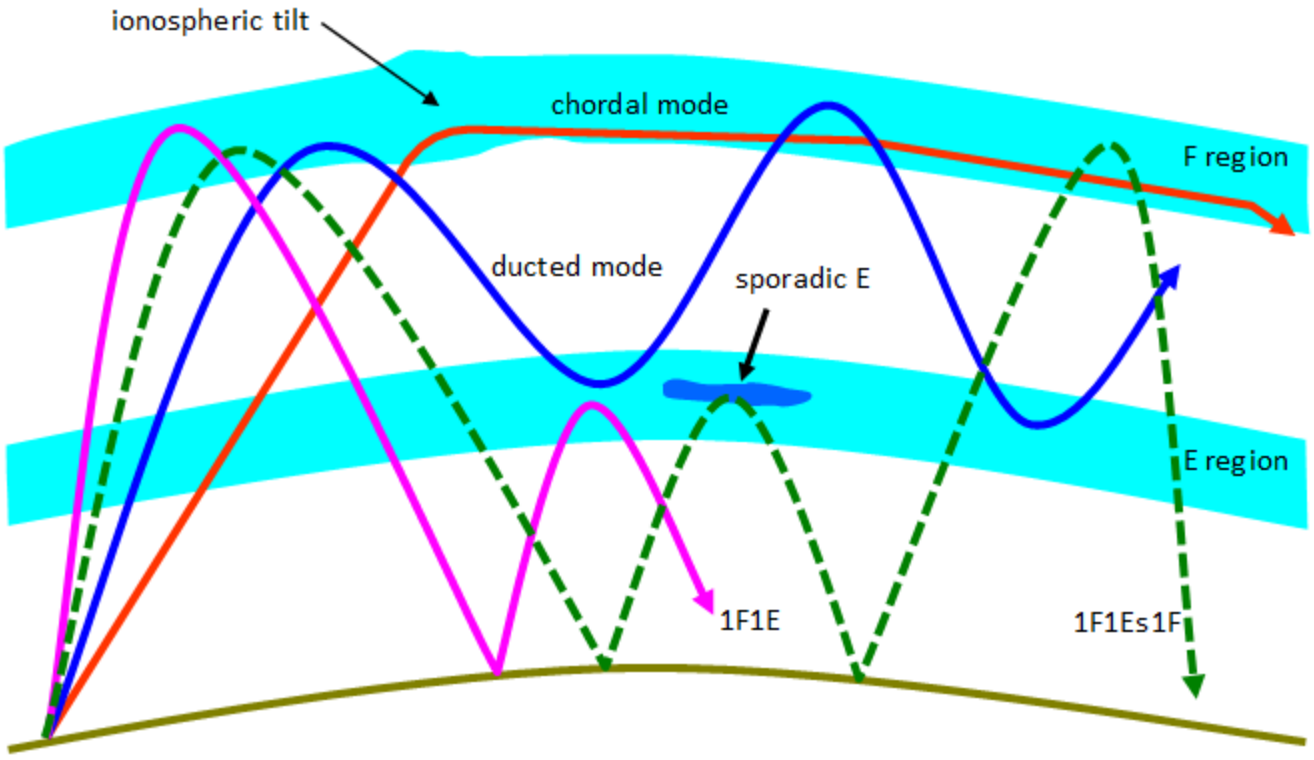
Ducting

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

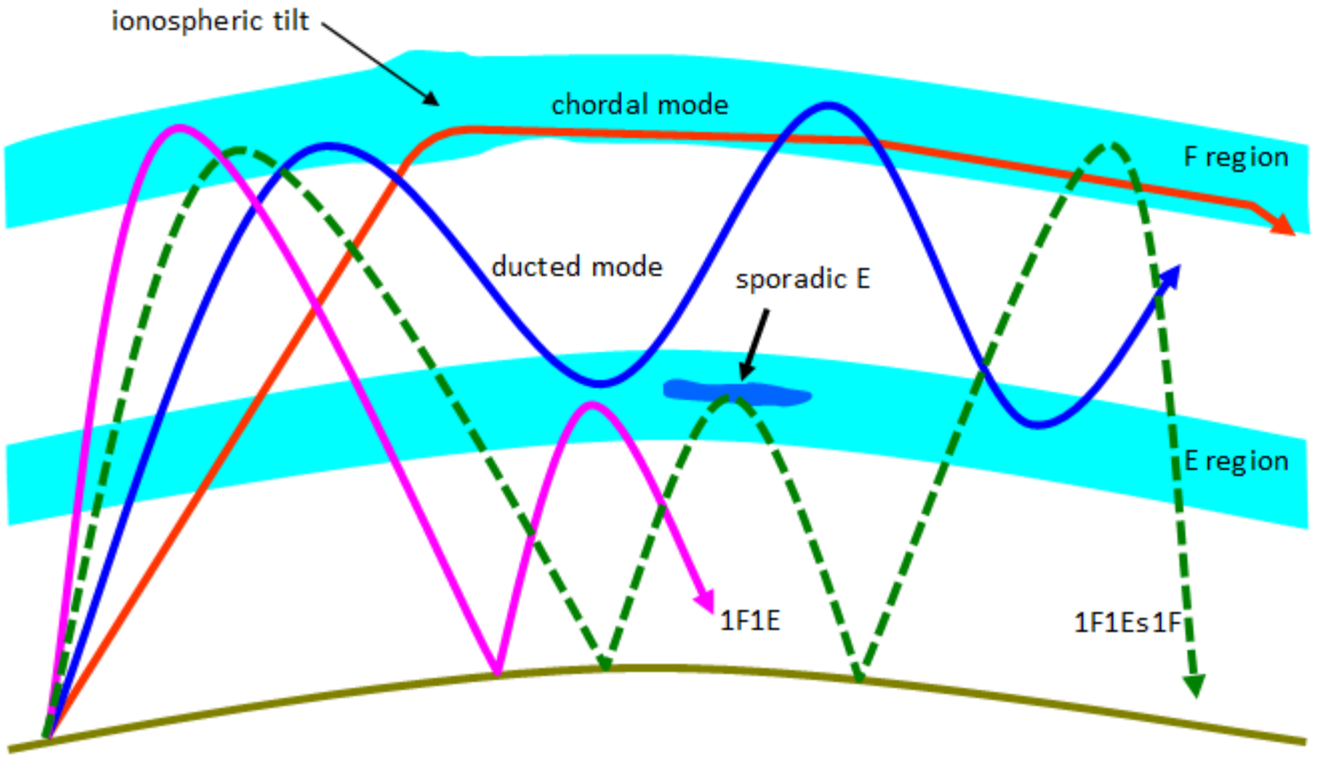
→ Waveguide behavior between E and F layers



[2] Australian Space Weather Forecasting Centre

Other exotics

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



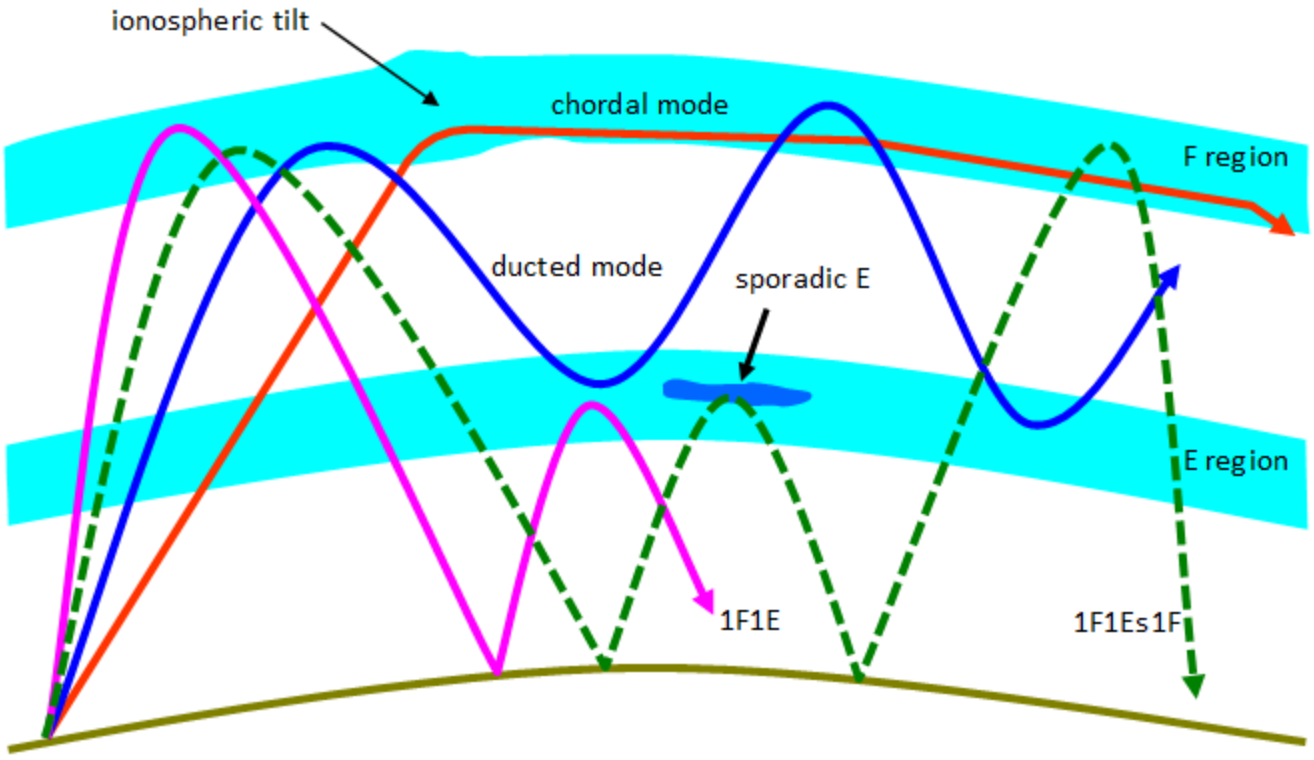
[2] Australian Space Weather Forecasting Centre

DEFENSIE
LA DÉFENSE

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



[2] Australian Space Weather Forecasting Centre

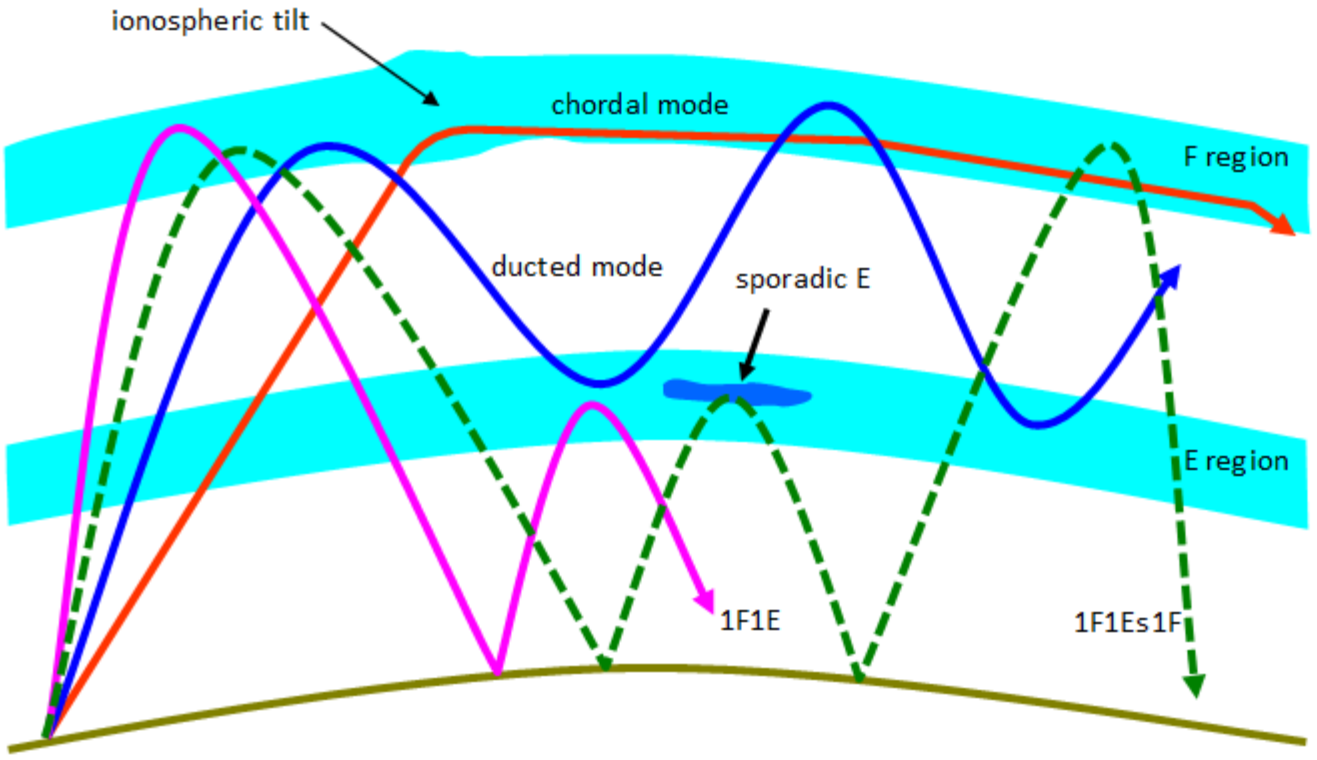
DEFENSIE
LA DÉFENSE

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



[2] Australian Space Weather Forecasting Centre

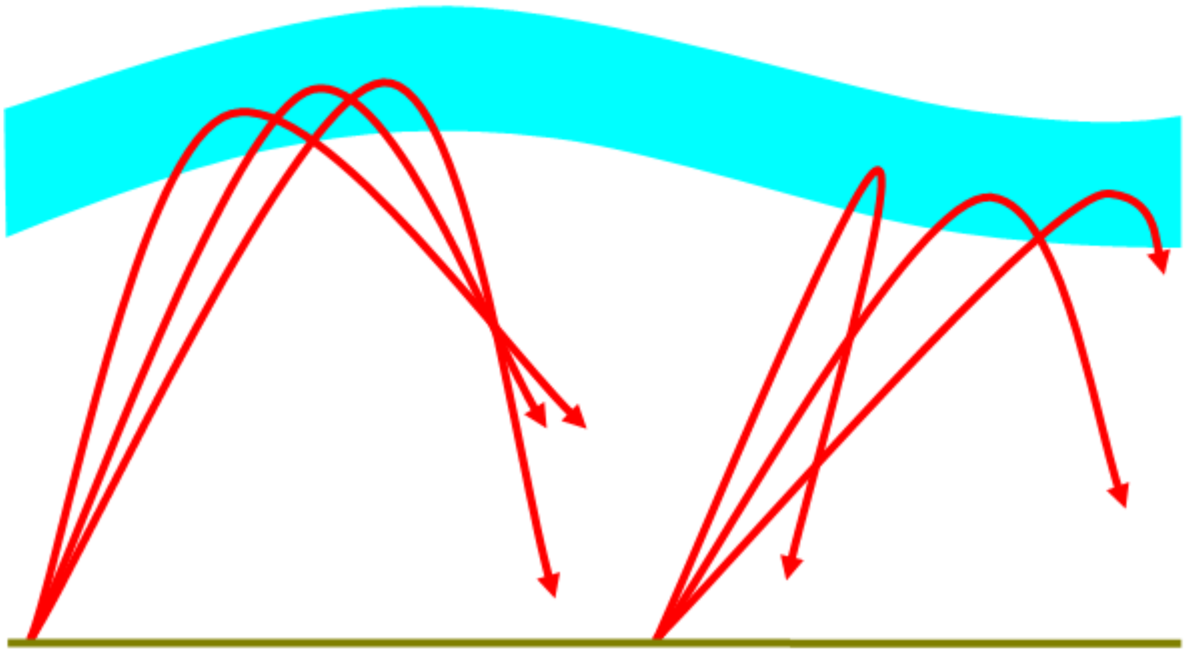
Traveling Ionospheric Disturbances (TIDs)

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



[2] Australian Space Weather Forecasting Centre

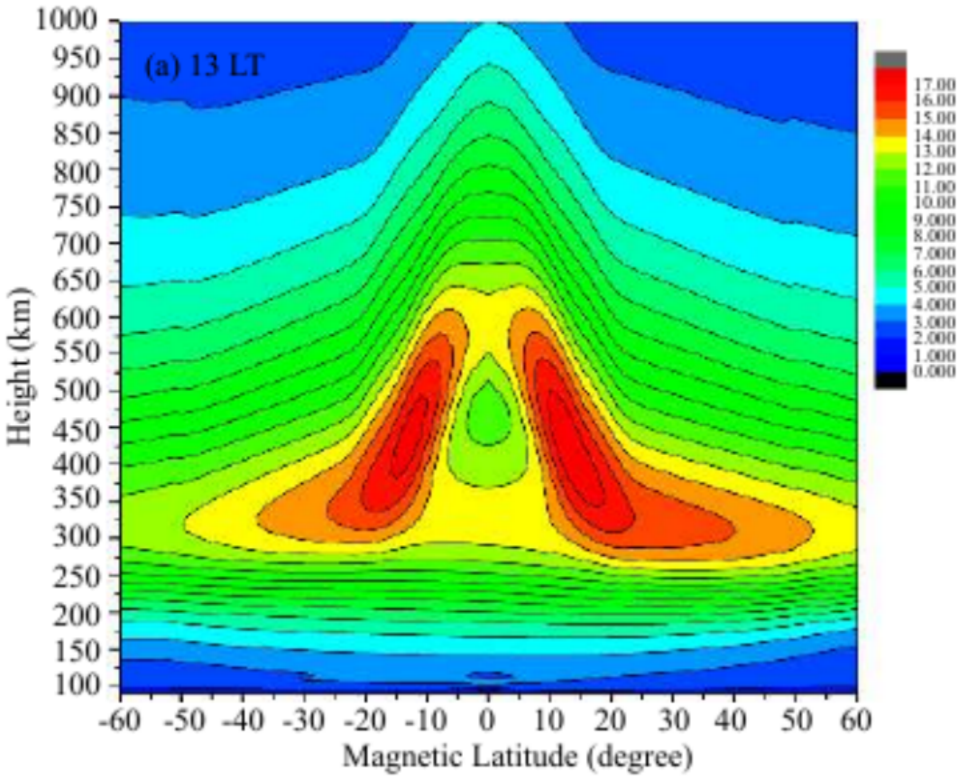
DEFENSIE
LA DÉFENSE

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

DEFENSIE
LA DÉFENSE

Transequatorial propagation (TEP)

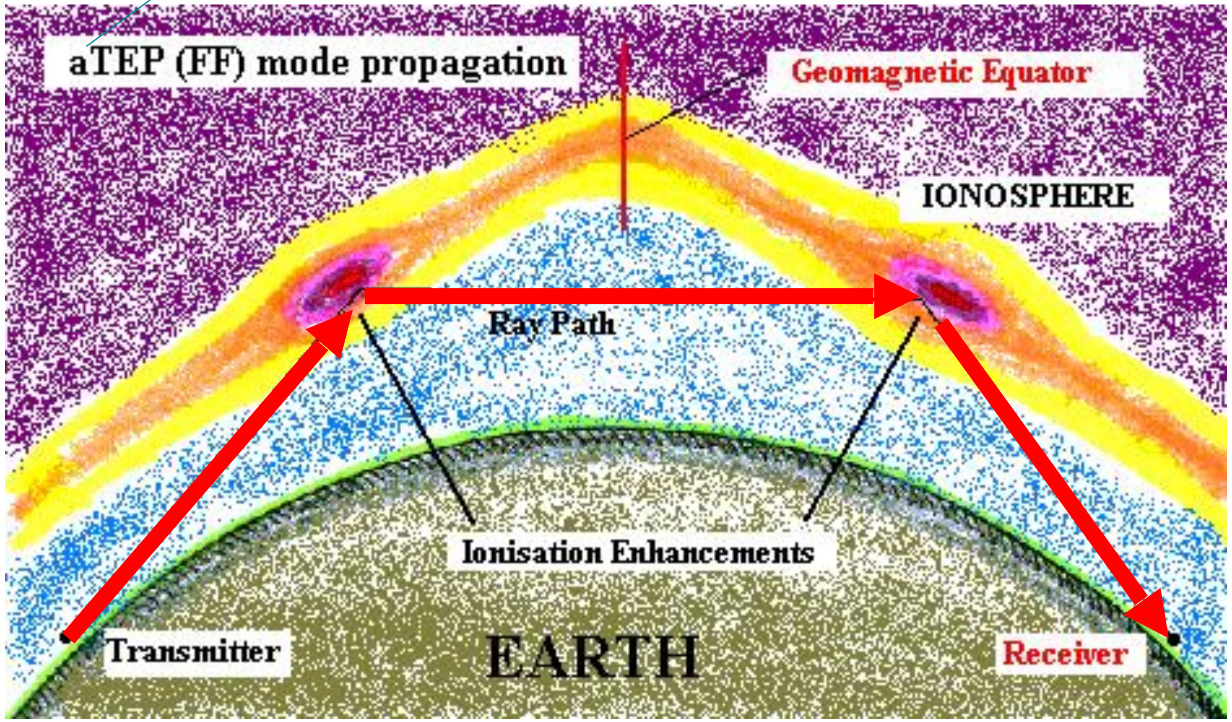
Can occur during the afternoon, when the anomaly is sufficiently built up.

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 ↔ South direction
  - Without passage through the D layer

- Wave hits ionosphere with a very shallow angle → MUF typically 15 to 25 MHz above typical values
  - MUF of 60 MHz has been observed

afternoon



[2] Australian Space Weather Forecasting Centre

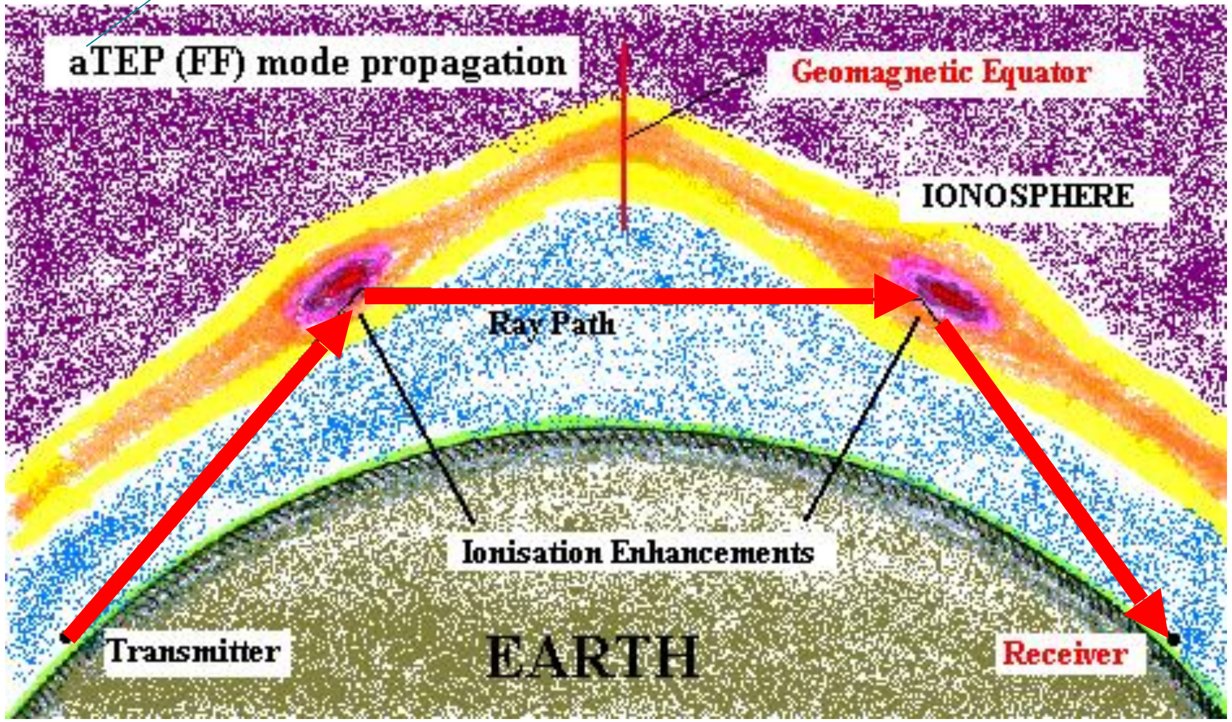
DEFENSIE
LA DÉFENSE

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.

afternoon



[2] Australian Space Weather Forecasting Centre

DEFENSIE
LA DÉFENSE

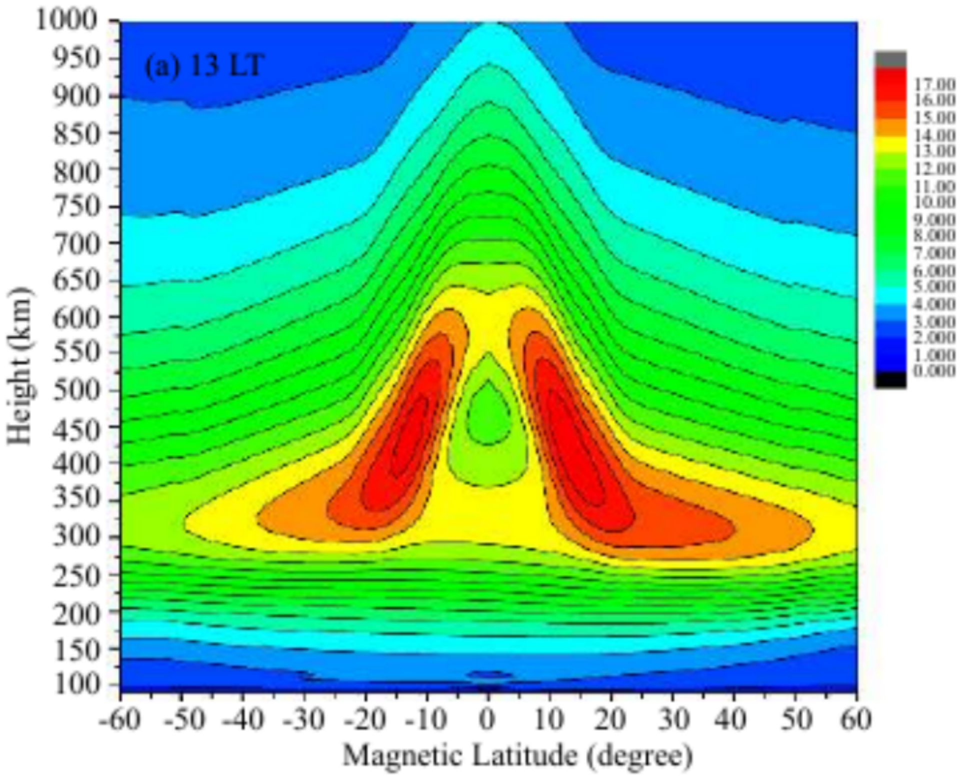
NVIS at low latitudes

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

DEFENSIE
LA DÉFENSE

DEFENSIE
LA DÉFENSE

VHF-UHF-SHF-EHF

VHF, UHF and up

Typically, frequencies on VHF & UHF operate in Line of Sight (LoS)
→ The higher the antenna, the further the reception

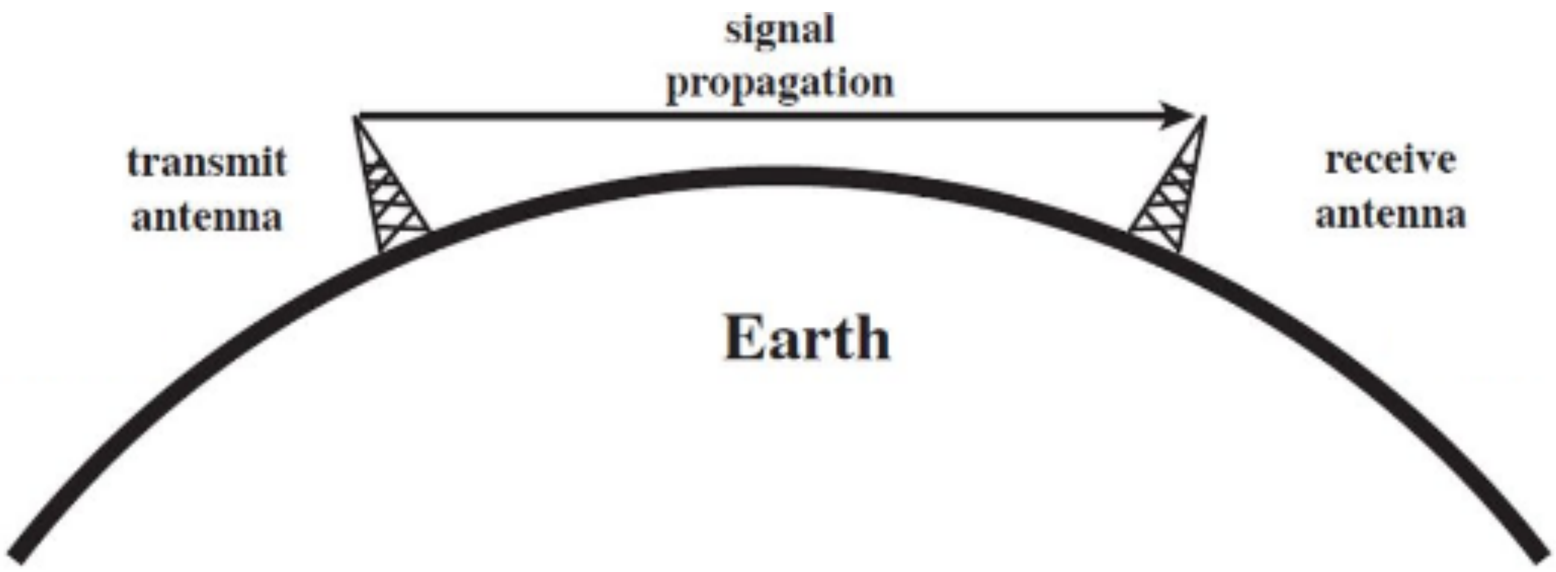
Some BLOS operation can occur due to:
- Tropospheric ducting
- Sporadic E events
- For VHF: a highly ionized ionosphere on a long path (just a high MUF due to a very low wave incidence angle)

DEFENSIE
LA DÉFENSE

Line of Sight (LOS)

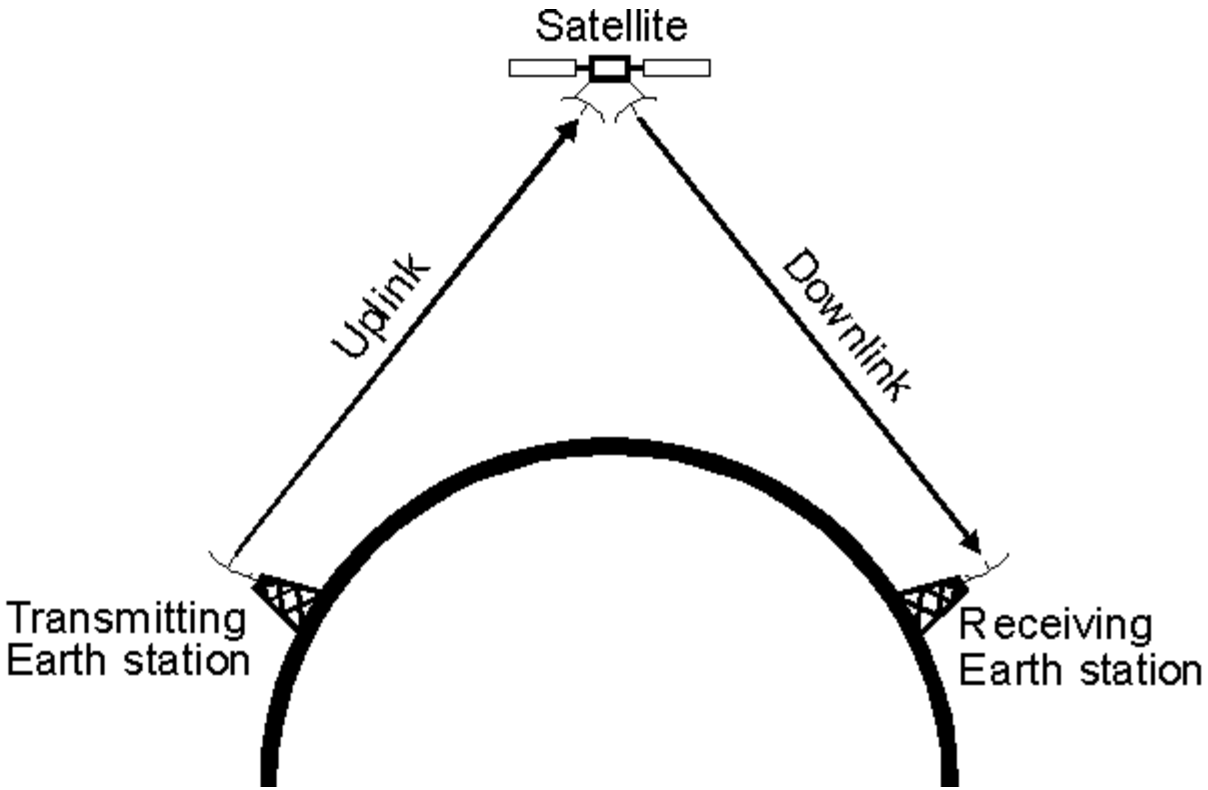
HF/VHF/UHF/SHF/EHF (3 MHz < f < 300 GHz (and up))

Fading effects due to interference between direct path, ground reflection, reflection against terrain/buildings, diffraction byproducts…



[1]: SWIC 2024 – STCE, RNLAF & KNMI

Line of Sight (LOS)



More on SATCOM later on…

[1]: SWIC 2024 – STCE, RNLAF & KNMI

DEFENSIE
LA DÉFENSE

Tropospheric ducting

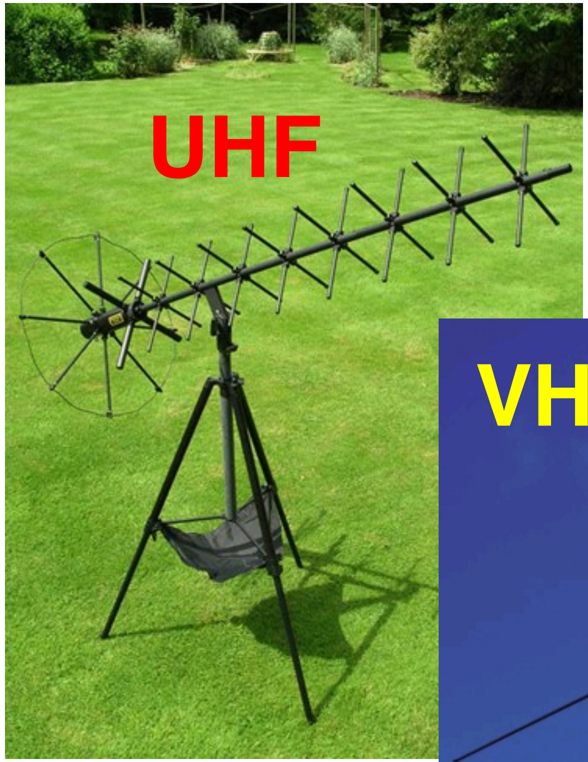
- Difference in refractive index between air layers
- In case of temperature inversion
  - Surface air is cooler than air at higher altitude (mist banks, shore air currents, evening, morning, …)
  - More common in flat terrain, sea, shore
  - Mountainous/undulating terrain might form barrier
- Lasts a few minutes up to hours
- Most prevalent around 100 MHz, but possibly present in a large bandwidth throughout the bands, also higher up in frequency
- Remember: the higher the frequency, the higher the free space loss

Sporadic E events (aka E skip)

- May cause ionospheric operation over extreme distances at VHF and UHF
- Ionisation caused by presence of metals due to meteors, volcanic eruptions, rocket exhaust products etc.
    - Frequency depending on ion concentration (which translates to a CUF of the ion trail)
    - Often very localized
- Lasts a few minutes up to hours

Further reading:
https://rsgb.org/main/get-started-in-amateur-radio/operating-your-new-station/vhfuhf-propagation/
https://3fs.net.au/tropospheric-propagation/
https://www.engineeringradio.us/blog/2010/05/e-skip-tropospheric-ducting-and-other-vhf-propagation-phenomena/
https://en.wikipedia.org/wiki/Tropospheric_propagation

VHF, UHF & SHF antennas



[1]: SWIC 2024 – STCE, RNLAF & KNMI

Different bands & purposes

Name	Frequency range	Applications
Low frequency	30 to 300 kHz	Navigation, time standards
Medium frequency	300 kHz to 3 MHz	Marine/aircraft navigation, AM broadcast
High frequency (shortwave)	3 to 30 MHz	Broadcasting, mobile radio, amateur radio
Very high frequency	30 to 300 MHz	Landmobile,FM/TVbroadcast,amateurradio
Ultra-high frequency	300 MHz to 3 GHz	Cell phones, mobile radio, WLAN, personal-area networks (PANs)
Super-high frequency	3 to 30 GHz	Satellite, radar, backhaul, TV
Extremely high frequency	30 to 300 GHz	Satellite, radar, backhaul, experimental

WAVEGUIDE

GROUNDWAV
E

SKYWAVE

Line-of-Sight

[1]: SWIC 2024 – STCE, RNLAF & KNMI

DEFENSIE
LA DÉFENSE

SATCOM

Transionospheric links

Impact of the ionosphere on SATCOM

Two main mechanisms:

- Static ionospheric **delay**
  - Dense ionization delays the signal
  - Delay is frequency dependent: dual frequency use removes the issue

- Ionospheric **scintillation** effects
  - Rapid modification of the radio signal due to the ionosphere

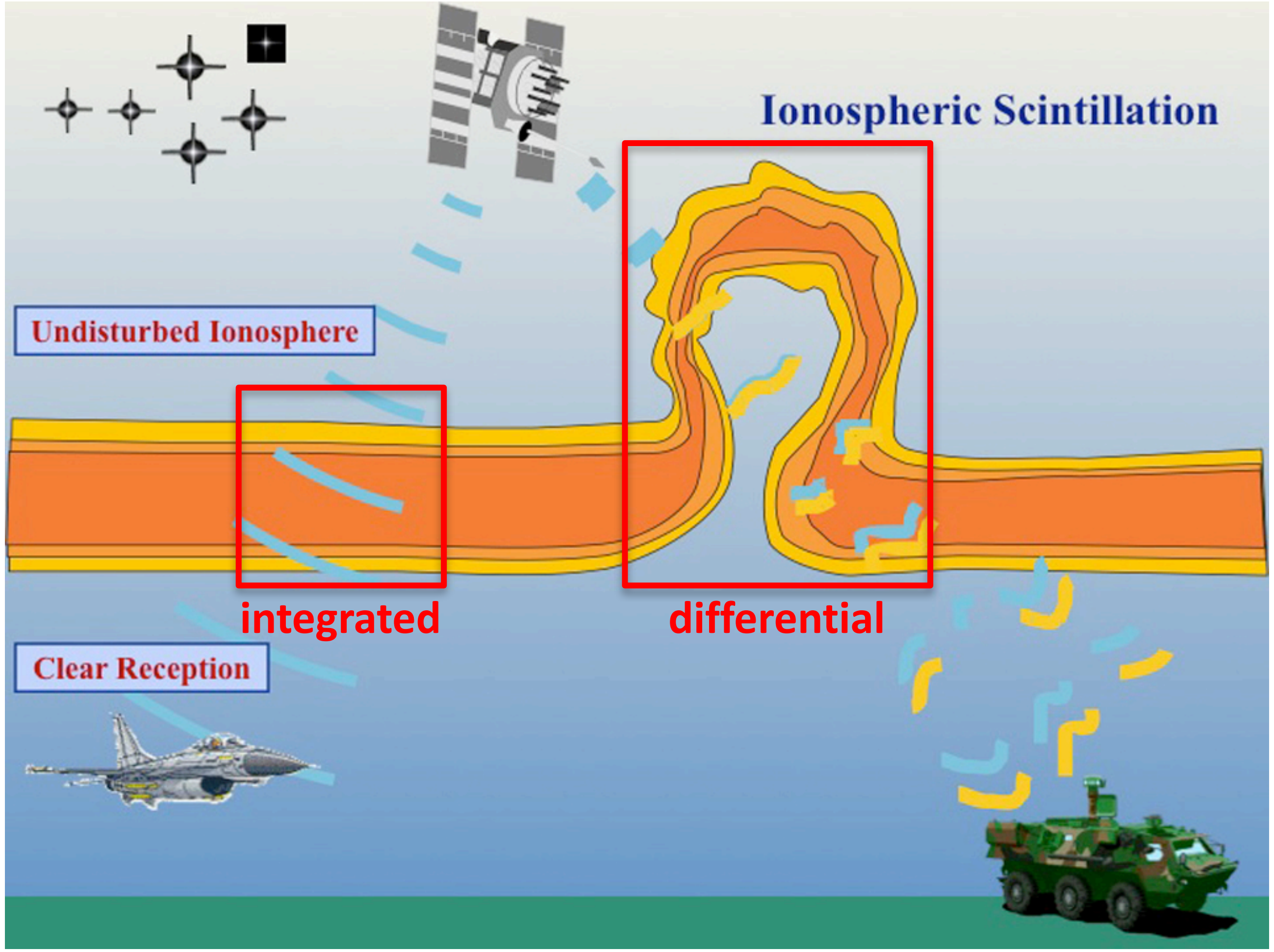
$$d_I \approx \frac{K}{f^2} \int n_e ds = \frac{K}{f^2} TEC^{slnt}$$

d_I	**Ionospheric delay**
K	**Constant**
F	**Frequency**
TEC^{slnt}	**Slanted Total Electron content: Amount of electrons between satellite and RX**

[1]: SWIC 2024 – STCE, RNLAF & KNMI

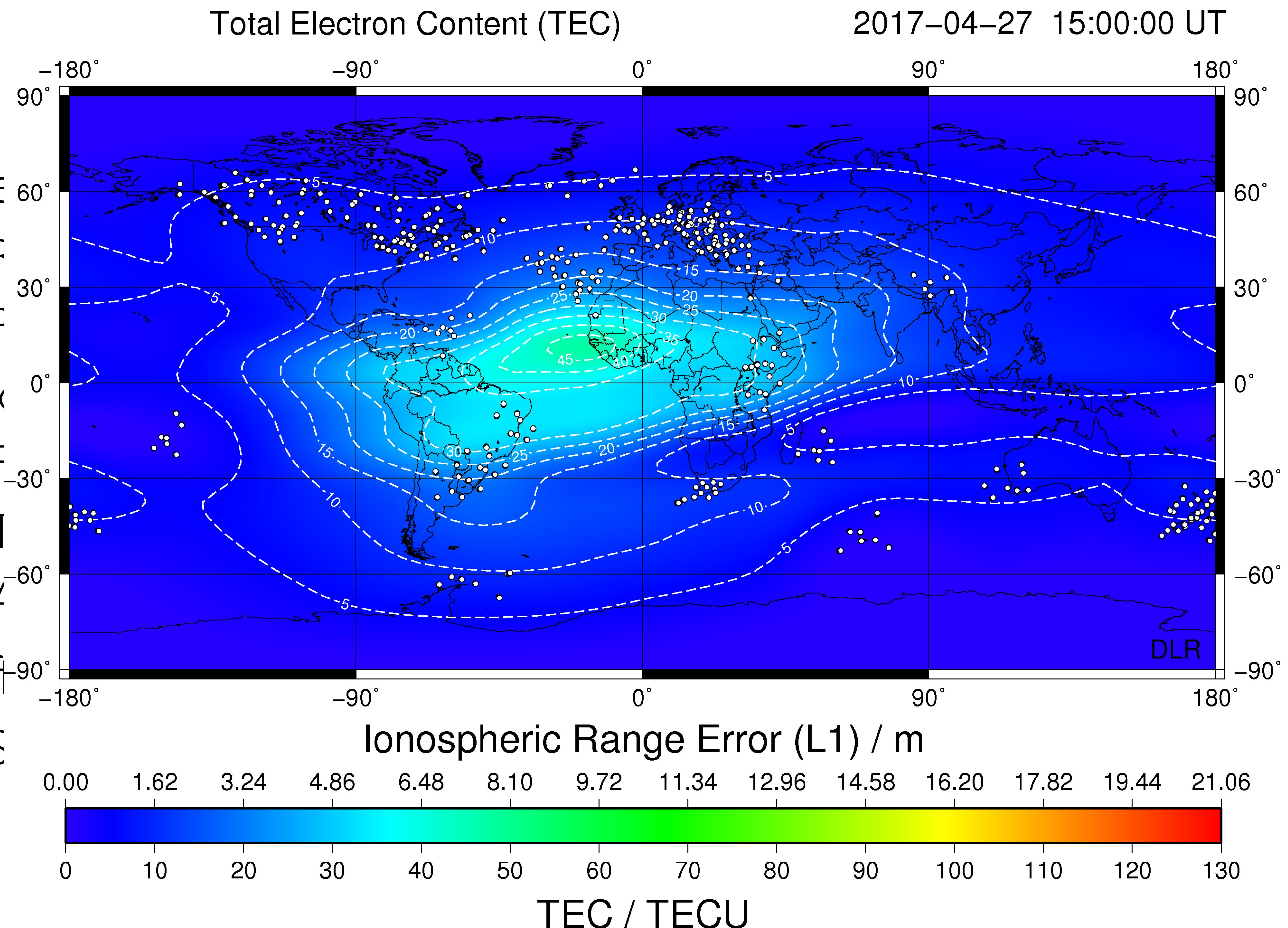
DEFENSIE
LA DÉFENSE

IMPACT OF SPWX
IONOSPHERIC – EARTH-SPACE



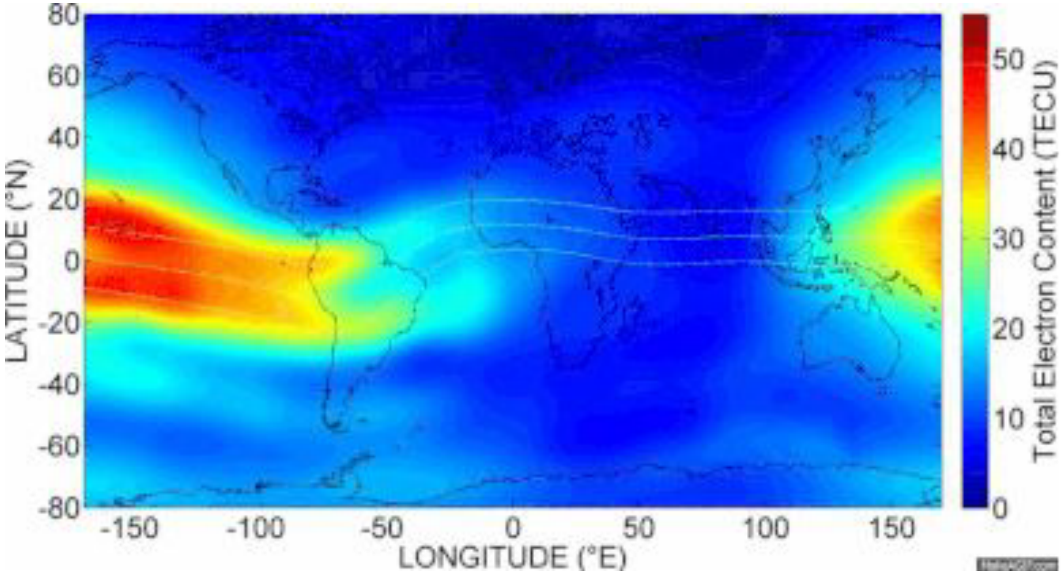
[1]: SWIC 2024 – STCE, RNLAF & KNMI

- Inte
  - F
  - F
  - I(
  - F
  - T
  - A
- Dif
  - S



Scintillation

- Plasma irregularities cause signals passing through them to fluctuate in amplitude and phase
  → scintillation
- Primarily in the polar regions & equator
- Also very large gradients in TEC ionospheric delay
  → increase in residual errors
- Polar regions: aurora / substorms
- Low geomagnetic latitudes: Equatorial Anomaly
  - At evening, the heavily ionized bulges dissipate, leaving empty "pockets"
  - Very irregular structures cause significant scintillation



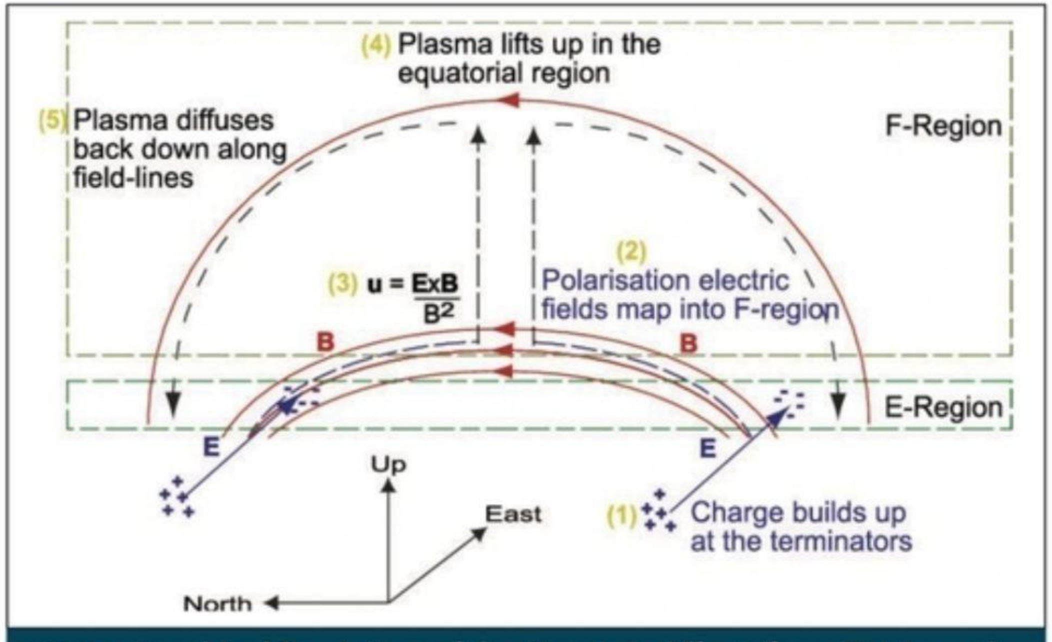
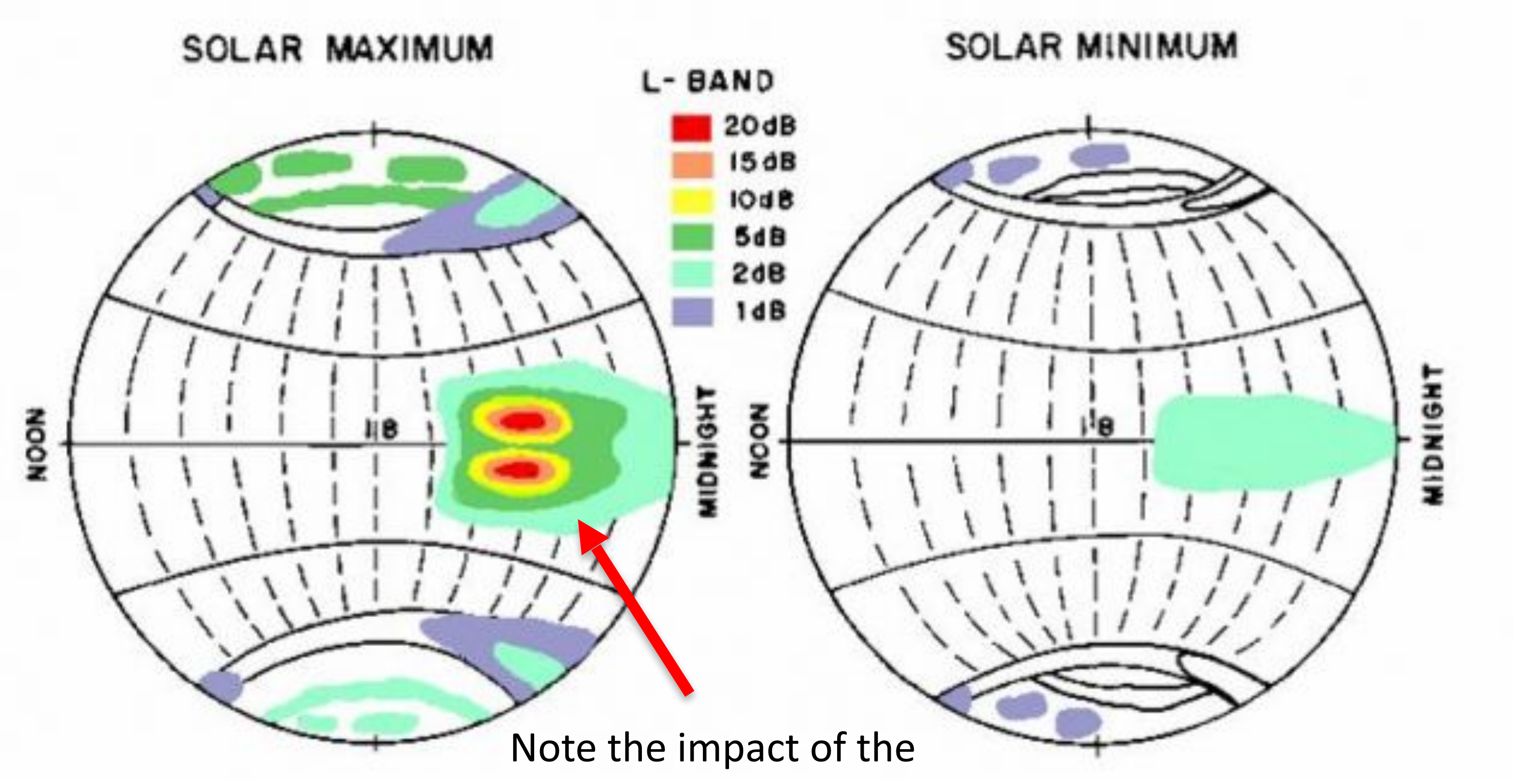


FIGURE 2 Graphical Depiction of the Fountain Effect (from T. J. Immel

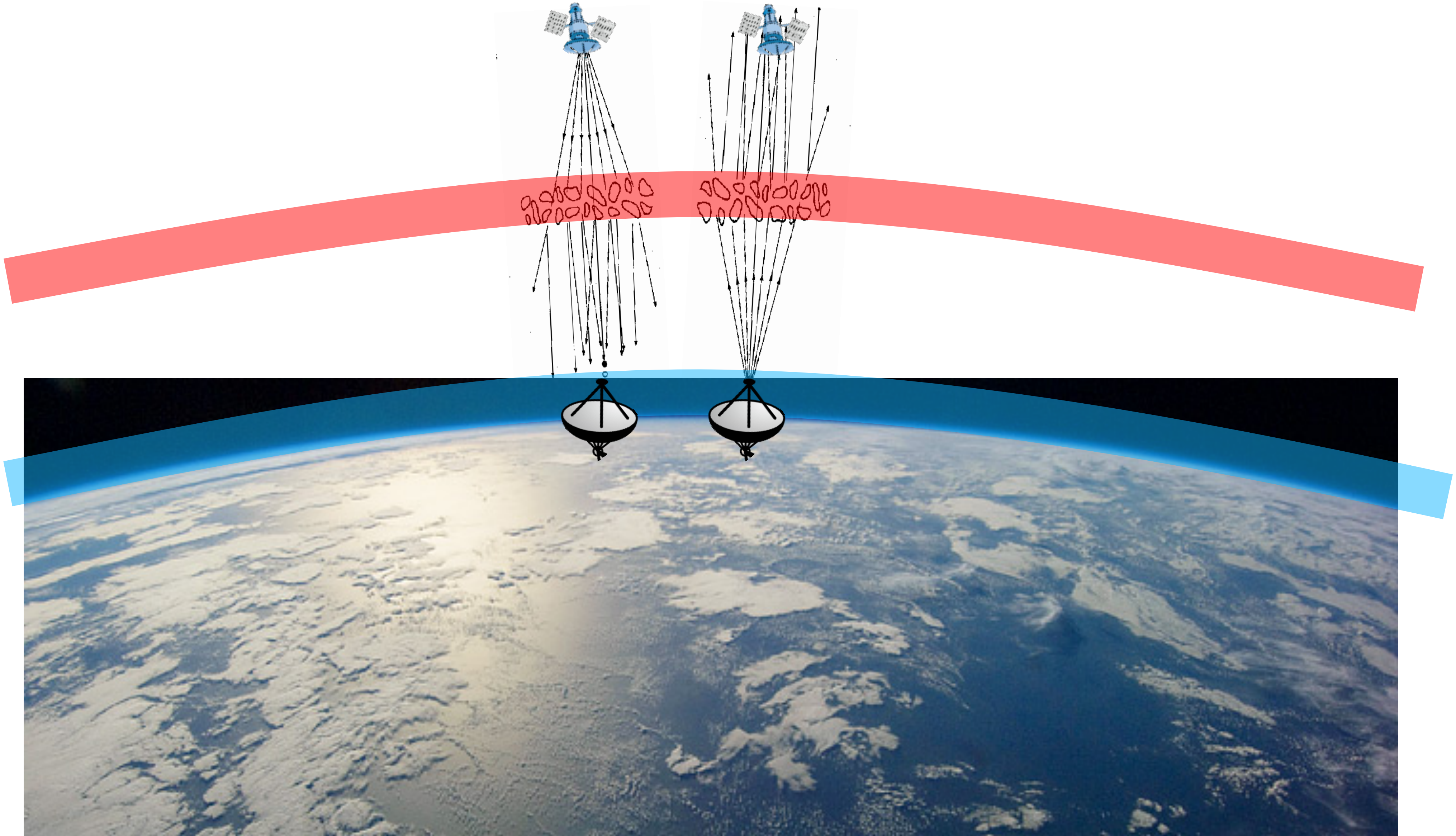
IMPACT AT UHF/SHF/EHF (LOS)
IONOSPHERIC SCINTILLATION



Note the impact of the equatorial anomaly in the evening!

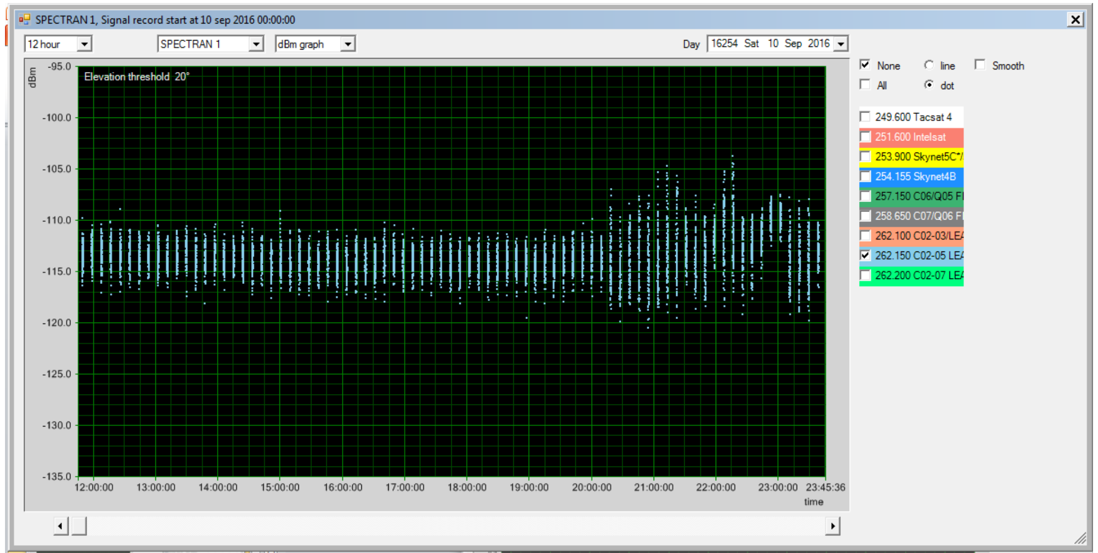
IONOSPHERIC SCINTILLATION

CAUSE



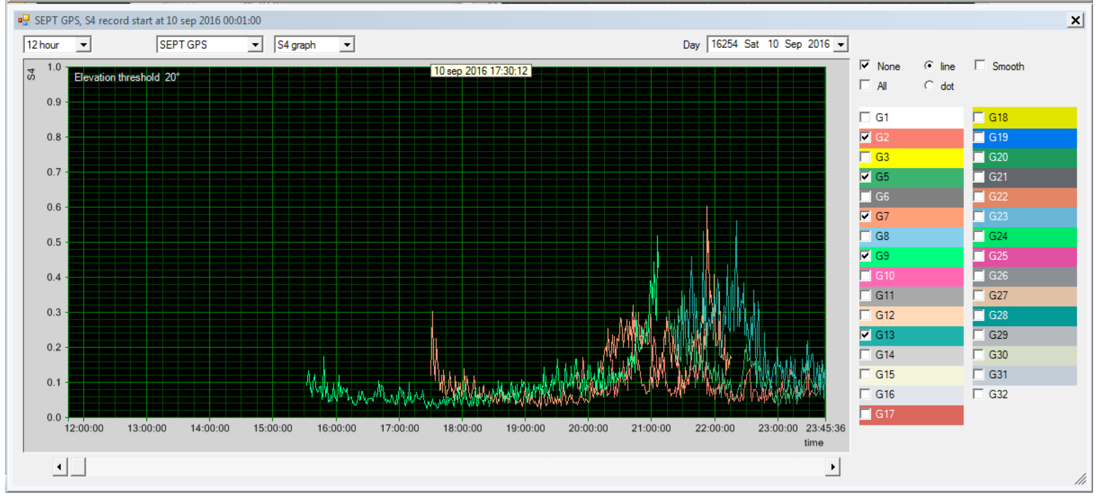
IONOSPHERIC SCINTILLATION EFFECT

UHF SATCOM



Fluctuating signal power

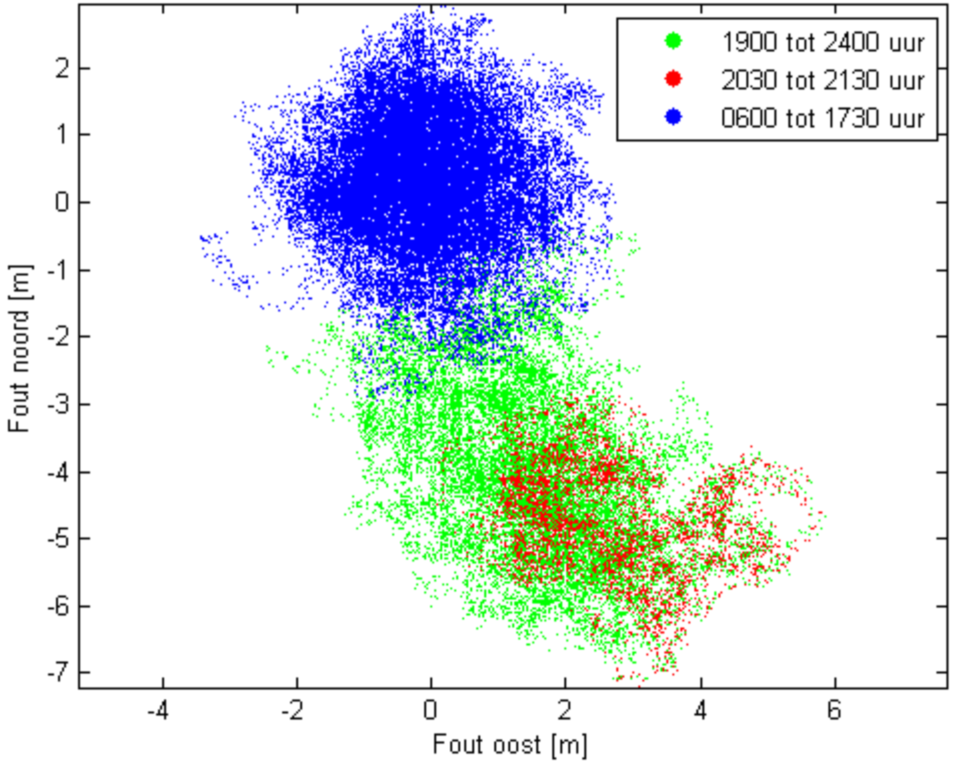
GPS L1



Scintillation

IONOSPHERIC SCINTILLATION
OPERATIONAL IMPACT (GPS)

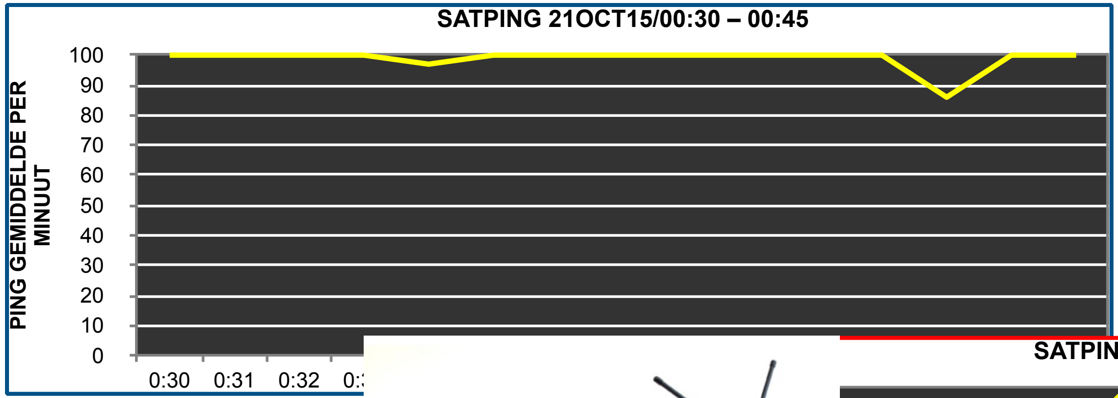
no scintillation



light scintillation

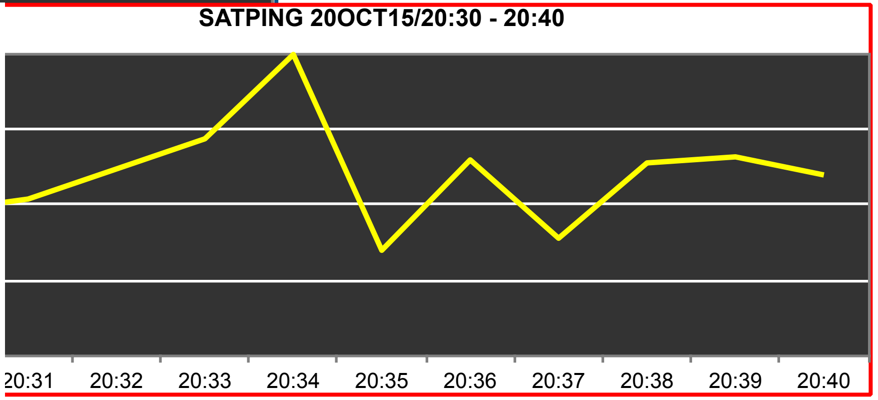
moderate scintillation

IONOSPHERIC SCINTILLATION
OPERATIONAL IMPACT (TACSAT)



no

scintillation



DEFENSIE
LA DÉFENSE

Q&A

In case all else fails

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