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

March 17th, 2026

DEFENSIE
LA DÉFENSE

Radio communication

DEFENSIE
LA DÉFENSE

1. General radio insights

Signal to noise ratio

Does a signal "connect"?
Means: Is the RX modem able to decode it?

$$SNR = \frac{P_{signal}}{P_{noise}}$$

→ Depends on the signal quality

→ Often expressed as Signal to Noise Ratio (SNR) [dB]

Many sources contribute to electromagnetic noise

- Power lines, windmills, power groups, …
- Electronics: power electronics, wireless charging, EV charging, LED / TL tubes, …
- Atmospheric & ionospheric noise
- Internal noise of the radio

RX should receive from locations with little noise
TX should get enough power towards RX

TX: Transmitter
RX: Receiver

DEFENSIE
LA DÉFENSE

SNR vs waveform

$P_{signal} \approx P_{noise}$

What SNR is required for succesful link?

Depends on the “ambition”, hence on the used waveform

High data rate? → high signal quality required
Low signal quality available? → low data rate

Some examples of HF waveforms

Note that these data rates are small.
The reason is that an HF channel is only 3 kHz wide

Wave Form ID	3 kHz	SNR Range in dB (Mid-Lat Skywave)
1 - 2PSK	150	>= 0
2 - 2PSK	300	>= +2
3 - 2PSK	600	>= +5
4 - 2PSK	1,200	>= +7
5 - 2PSK	1,600	>= +8
6 - 4PSK	3,200	>= +11
7 - 8PSK	4,800	>= +14
8 - 16QAM	6,400	>=+17
9 - 32QAM	8,000	>+=20
10 - 64QAM	9,600	>=+23
11 - 64QAM	12,000	>=+25
12 - 256QAM	16,000	>=+28

DEFENSIE
LA DÉFENSE

SNR vs waveform: wideband

Low datarate may be improved by increasing bandwidth

→ Not trivial from a technical viewpoint
→ Not trivial spectrum wise

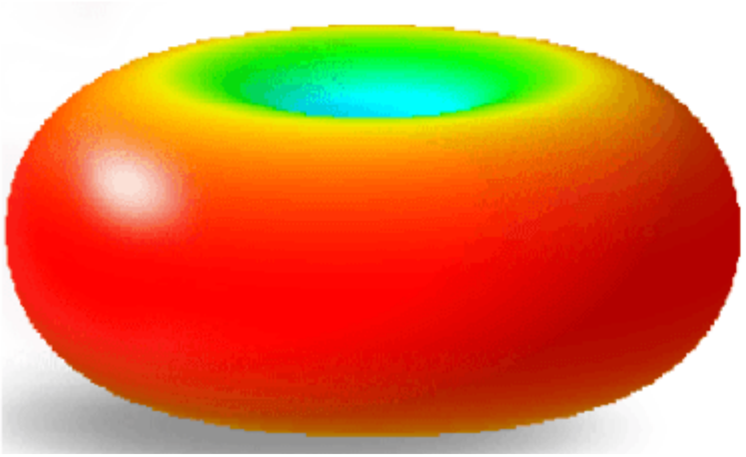
Wave Form ID	3 kHz	6 kHz	9 kHz	12 kHz	15 kHz	18 kHz	21 kHz	24 kHz	30 kHz	36 kHz	42 kHz	48 kHz	SNR Range in dB (Mid-Lat Skywave)
1 - 2PSK	150	300	600	600	600	1,200	600	1,200	1,200	2,400	2,400	2,400	>= 0
2 - 2PSK	300	600	1,200	1,200	1,200	2,400	1,200	2,400	2,400	4,800	4,800	4,800	>= +2
3 - 2PSK	600	1,200	2,400	2,400	2,400	4,800	2,400	4,800	4,800	9,600	9,600	9,600	>= +5
4 - 2PSK	1,200	2,400	-	4,800	4,800	-	4,800	9,600	9,600	12,800	14,400	16,000	>= +7
5 - 2PSK	1,600	3,200	4,800	6,400	8,000	9,600	9,600	12,800	16,000	19,200	19,200	24,000	>= +8
6 - 4PSK	3,200	6,400	9,600	12,800	16,000	19,200	19,200	25,600	32,000	38,400	38,400	48,000	>= +11
7 - 8PSK	4,800	9,600	14,400	19,200	24,000	28,800	28,800	38,400	48,000	57,600	57,600	72,000	>= +14
8 - 16QAM	6,400	12,800	19,200	25,600	32,000	38,400	38,400	51,200	64,000	76,800	76,800	96,000	>=+17
9 - 32QAM	8,000	16,000	24,000	32,000	40,000	48,000	48,000	64,000	80,000	96,000	96,000	120,000	>+=20
10 - 64QAM	9,600	19,200	28,800	38,400	48,000	57,600	57,600	76,800	96,000	115,200	115,200	144,000	>=+23
11 - 64QAM	12,000	24,000	36,000	48,000	57,600	72,000	76,800	96,000	120,000	144,000	160,000	192,000	>=+25
12 - 256QAM	16,000	32,000	48,000	64,000	76,800	90,000	115,200	120,000	160,000	192,000	192,000	240,000	>=+28

Antenna pattern

Some antennas **radiate their power equally** towards all directions (when used as a TX)

They **receive power equally well** from all directions (when used as a RX)

These are <u>omnidirectional antennas</u>

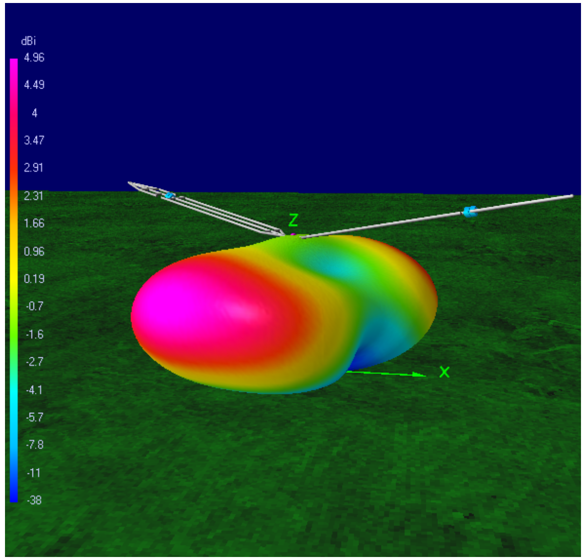


Antenna pattern

Some antennas **focus their power** more towards certain directions
(when used as a TX)

They also **receive power better** from those directions
(when used as a RX)
They **pick up less** from other directions

These are <u>directive antennas</u>



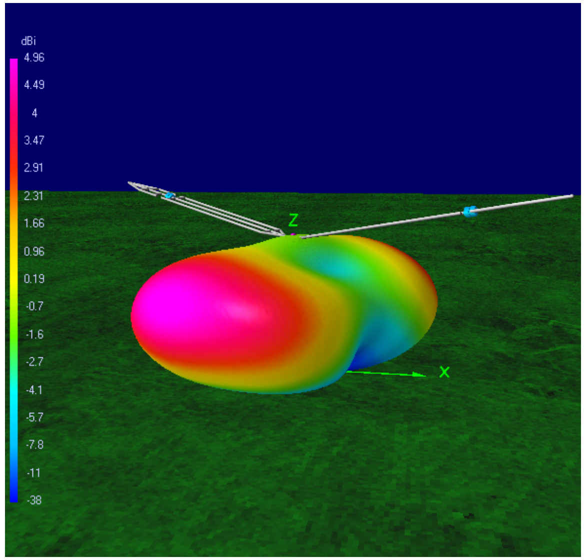
DEFENSIE
LA DÉFENSE

Antenna pattern

$$SNR = \frac{P_{signal}}{P_{noise}}$$

TX:
More power focused towards RX? → **Higher SNR**

RX:
Receives better from desired direction, and worse from the others?
→ Less noise & interference received from those directions
→ **Higher SNR**



DEFENSIE
LA DÉFENSE

2. Practicals & tacticals

Interception and detection

Modern electronic warfare technology makes it prudent to think:

“If you transmit, you are detected.”

“If you were detected, you could have been triangulated.”

→ Try to achieve just enough SNR for your RX to hear you
→ Try to radiate a signal strength too low for the opponent to detect you

→ Often not feasible

→ Use directive antennas whenever possible!

→ Low Probability of Intercept (LPI) waveforms exist, often wideband

→ Horrible datarate and wideband allows reception with crazy low SNR’s
… for someone with the right code, who knows what he’s looking for, at least…

Jamming

"The use of electronic warfare techniques to disrupt or interfere with enemy radar and communication systems"

Brute force: "Scream over" the actual signal that is to be received.

Smart jamming: e.g. exploiting guard intervals in WiFi
→ Sometimes at barely noticeable power levels

DEFENSIE
LA DÉFENSE

Spoofing

Emission of signals with fake content, stronger than that of the actual sender.

Often inflicted on radars or GNSS receivers

DEFENSIE
LA DÉFENSE

DEFENSIE
LA DÉFENSE

3. SWx vs. Mil systems

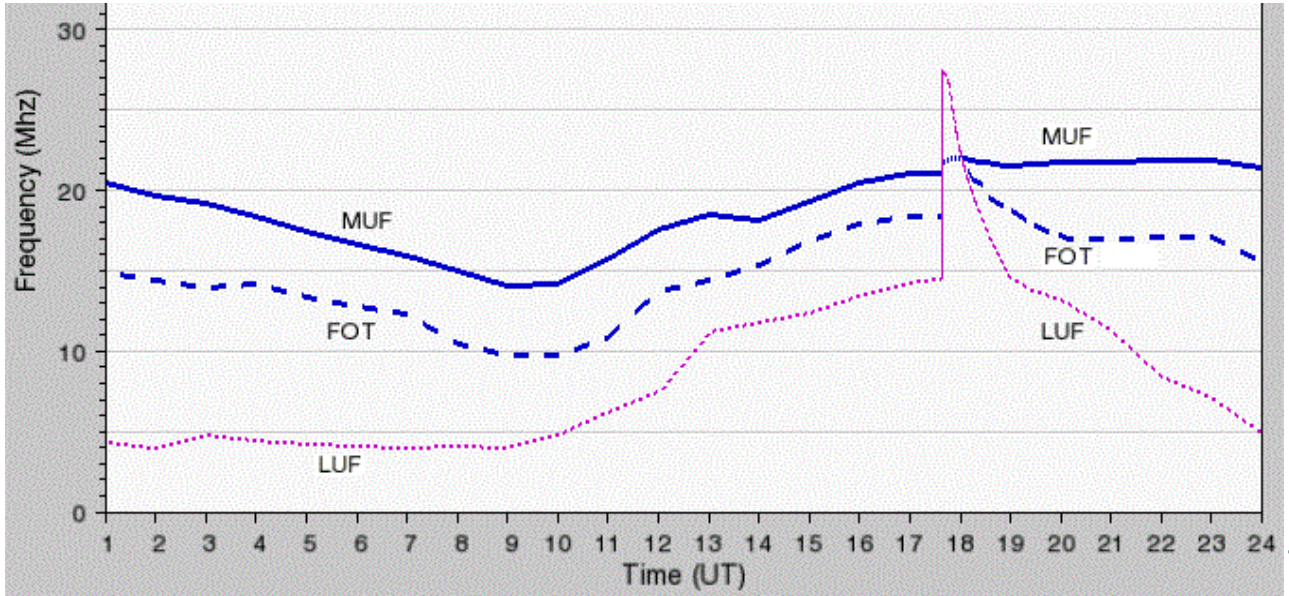
Mid geomagnetic latitudes

HF

- **X-ray flares** increase noise and LUF → Radio blackout (aka. short wave fade) (day side only)
- **Geomagnetic storms** lower MUF → Radio blackout

OTH radar:

- **X-ray flares** increase noise and LUF → No OTH capability
- **Geomagnetic storms** lower MUF → No OTH capability



Mid geomagnetic latitudes

HF

- **X-ray flares** increase noise and LUF → Radio blackout (aka. short wave fade) (day side only)
- **Geomagnetic storms** lower MUF → Radio blackout

OTH radar:

- **X-ray flares** increase noise and LUF → No OTH capability
- **Geomagnetic storms** lower MUF → No OTH capability
- **Ionospheric disruptions from earth** → Anomalous reflections

Radar:

- **Solar radiation bursts** (day side only) → False images

GNSS:

- **Geomagnetic storms**
- **Ionospheric disruptions from earth** → Severely impacted precision

DEFENSIE
LA DÉFENSE

High geomagnetic latitudes

All that applies on mid latitudes, plus:

SATCOM:
- **Geomagnetic storms** cause scintillation → Link loss

GNSS:
- **Geomagnetic storms** cause scintillation → GNSS inaccuracy

HF & OTH radar:
- **Geomagnetic storms** cause particle precipitation → Increased noise and LUF over the poles
- **Solar particle storms** cause particle precipitation → Increased noise and LUF over the poles

Radar & OTH radar:
- Reflections against **aurora** → Backscatter & anomalous reflections

Low geomagnetic latitudes

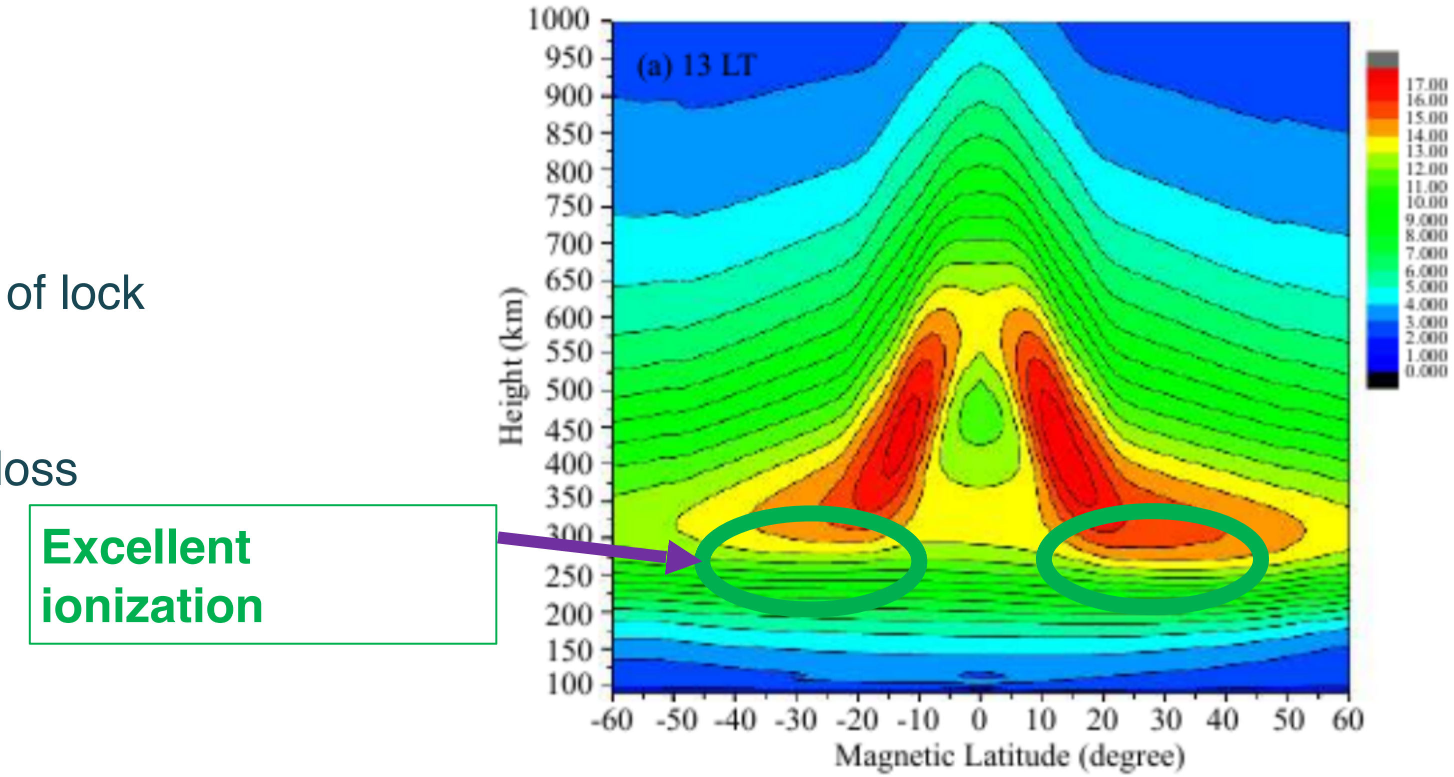
All that applies on mid latitudes, plus:

GNSS:

- **Post sunset scintillation** → Loss of lock

SATCOM:

- **Post sunset scintillation** → Link loss



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

Low geomagnetic latitudes

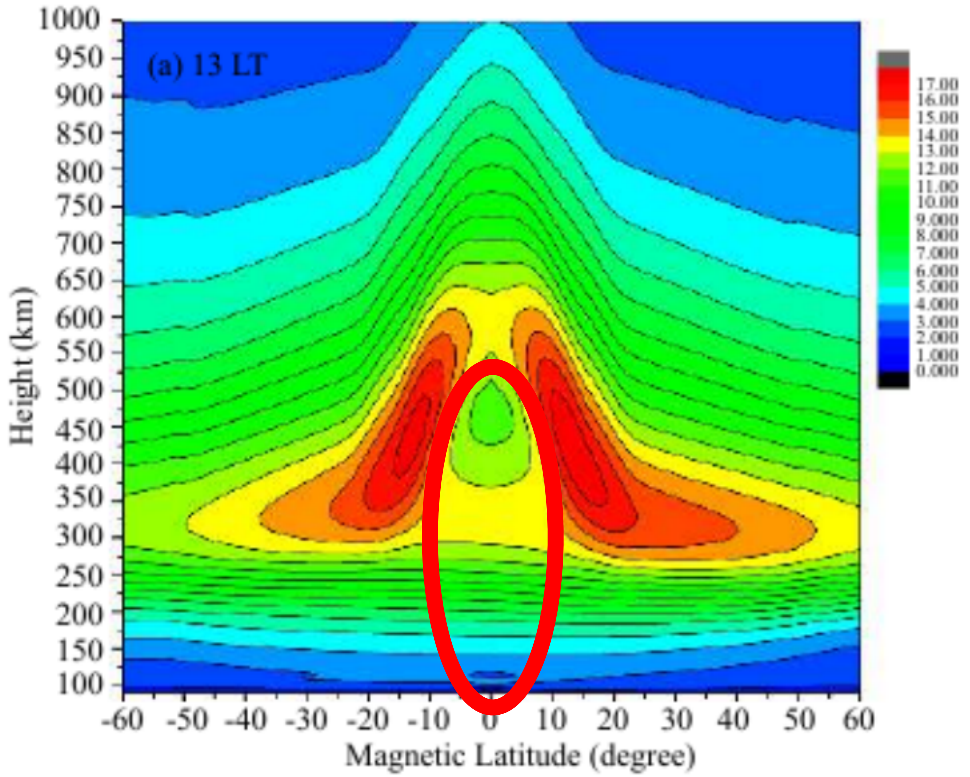
All that applies on mid latitudes, plus:

GNSS:
- **Post sunset scintillation** → Loss of lock

SATCOM:
- **Post sunset scintillation** → Link loss

HF:
- **Plasma bubbles cause multipath comms** → **“Chopped up” N**

OTH radar:
- Reflections against **plasma bubbles** → Anomalous reflections



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

DEFENSIE
LA DÉFENSE

DEFENSIE
LA DÉFENSE

4. HF links

And frequency selection

Frequency selection

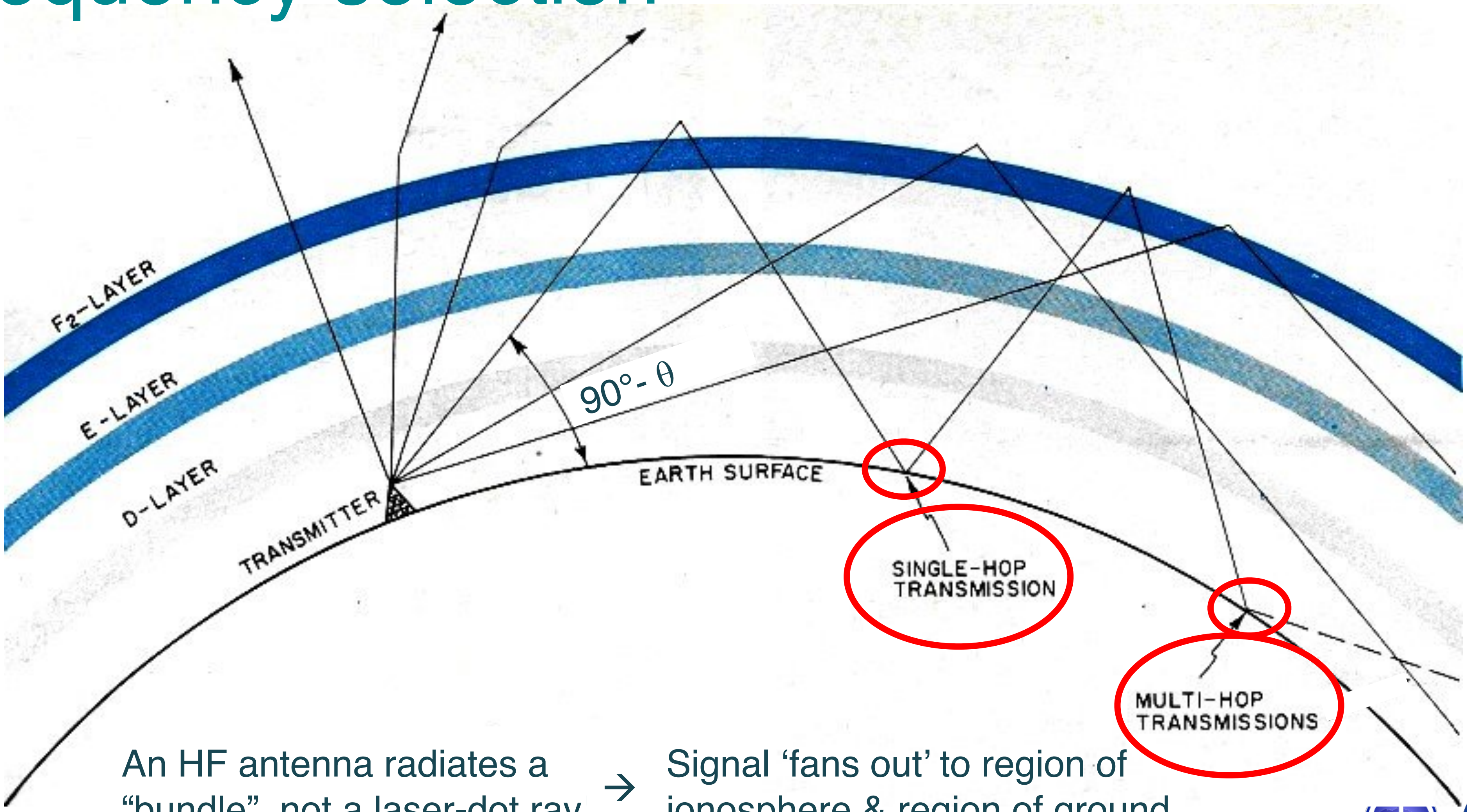
Where and how would the signal bounce against the ionosphere?

One hop is max ~3000 km
A grey circle on this figure is 3000 km

Map from http://ns6t.net

LA DÉFENSE

Frequency selection



An HF antenna radiates a "bundle", not a laser-dot ray → Signal 'fans out' to region of ionosphere & region of ground

Ionospheric-Propagation Predictions, April 1969 Electronics World - RF Cafe

DEFENSIE
LA DÉFENSE

Frequency selection

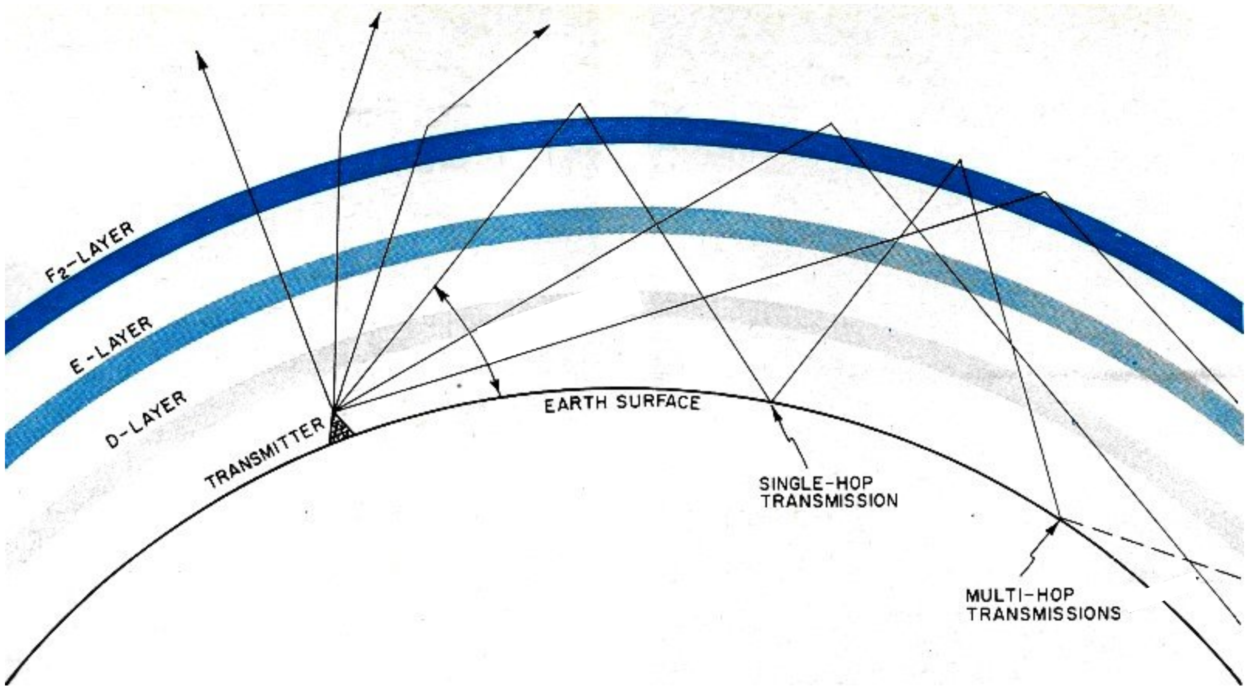
Always look at:

- State of the ionosphere (CUF)
- Distance of the desired link
    - Where and how would the signal bounce against the ionosphere?
    - On what terrain would the signal touch the ground?

From there, a MUF can be deducted

NVIS

Long range



Ionospheric-Propagation Predictions, April 1969 Electronics World - RF Cafe

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

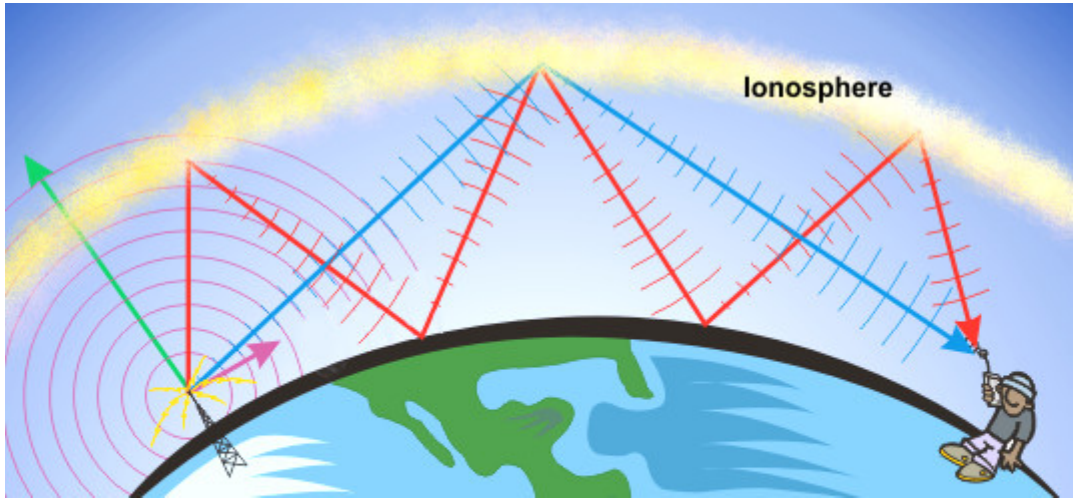
LA DEFENSE

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
→ North – South link is much harder than East-West link



[1]: SWIC 2024 – STCE, RNLAF & KNMI

DEFENSIE
LA DÉFENSE

Skip zone

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

Quiz:

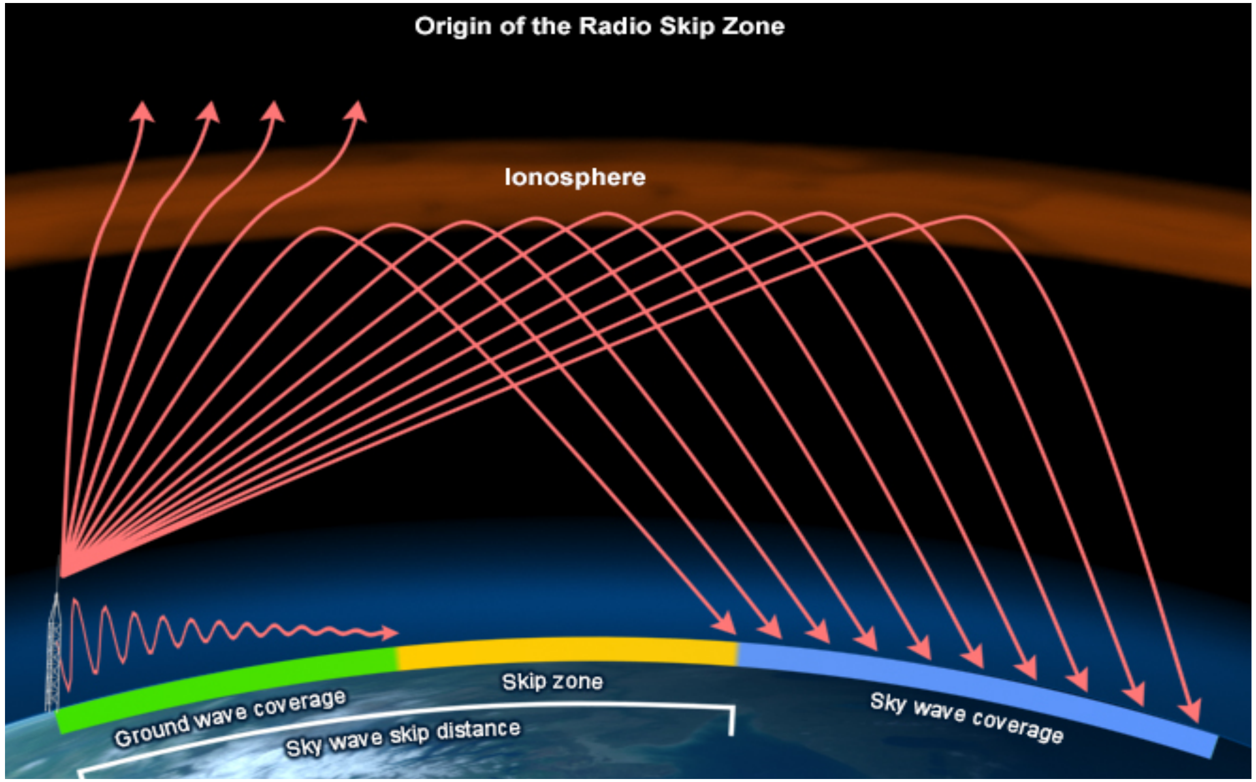
Suppose CUF is 3 MHz for the entire region.
You are allocated only use of 4 MHz.

Can you reach a receiver who is:

- 2000 km away?
  - Yes: MUF is definitely larger than 3 MHz for this link
- 200 m away?
  - Yes, line of sight
- 20 km away?
  - Probably yes: ground wave
- 200 km away?
  - Ground wave became too weak
  - MUF is not much higher than CUF!

} No link!

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



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

Excercise

Each circle is ~3000 km.

What terrain will we encounter when we wish to communicate:

With East Canada?
Number of hops?

With Türkiye?
Number of hops?

Map from http://ns6t.net

LA DÉFENSE

Excercise

Each circle is ~3000 km.

What terrain will we encounter when we wish to communicate:

With Afghanistan?
Number of hops?

With DR Congo?
Number of hops?

How to reach Congo?
Try the Grey Line

Map from http://ns6t.net

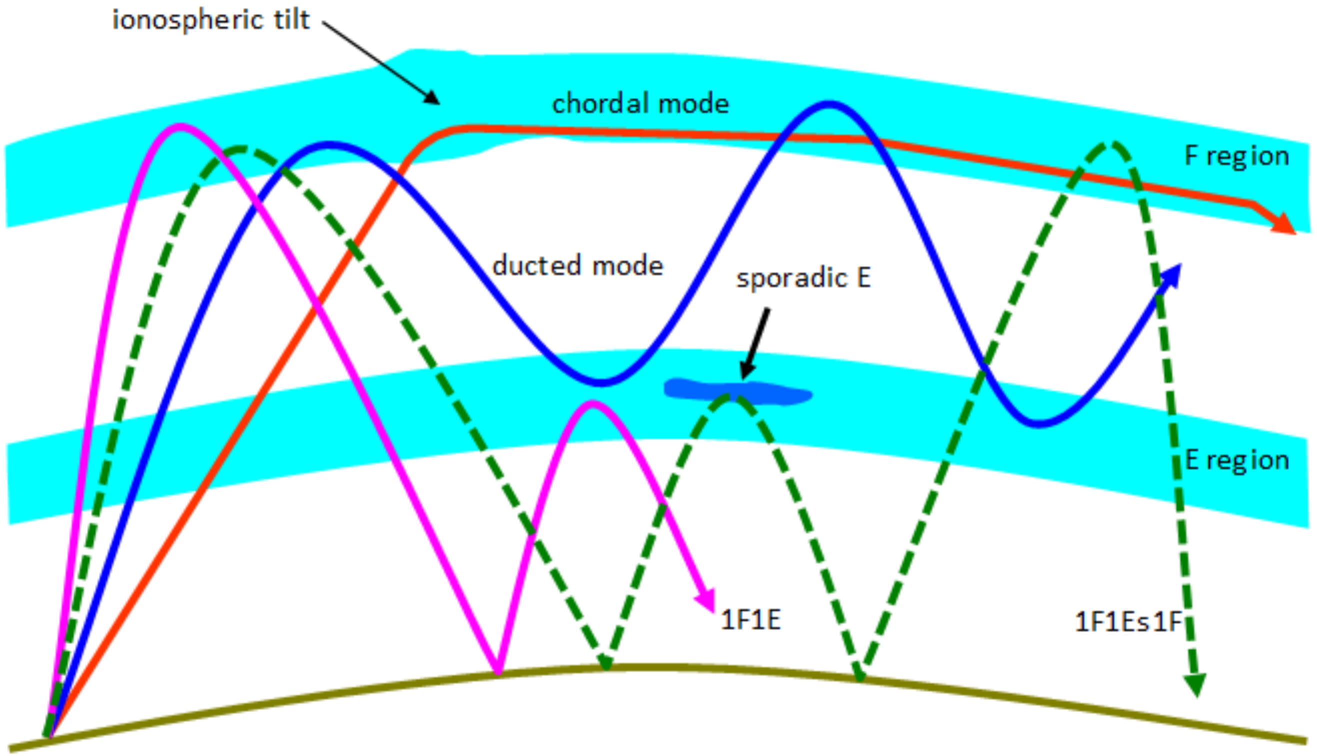
Greyline propagation (morning & evening)

e.g. Evening:
Decreasing ionization just above your head, but not yet at a low angle → those regions are still well-ionized by the sun.

Only faint D layer above your head, F still more intact.

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

With some luck: Chordal mode!



[2] Australian Space Weather Forecasting Centre

DEFENSIE
LA DÉFENSE

DEFENSIE
LA DÉFENSE

CUF above Belgium

Low solar cycle

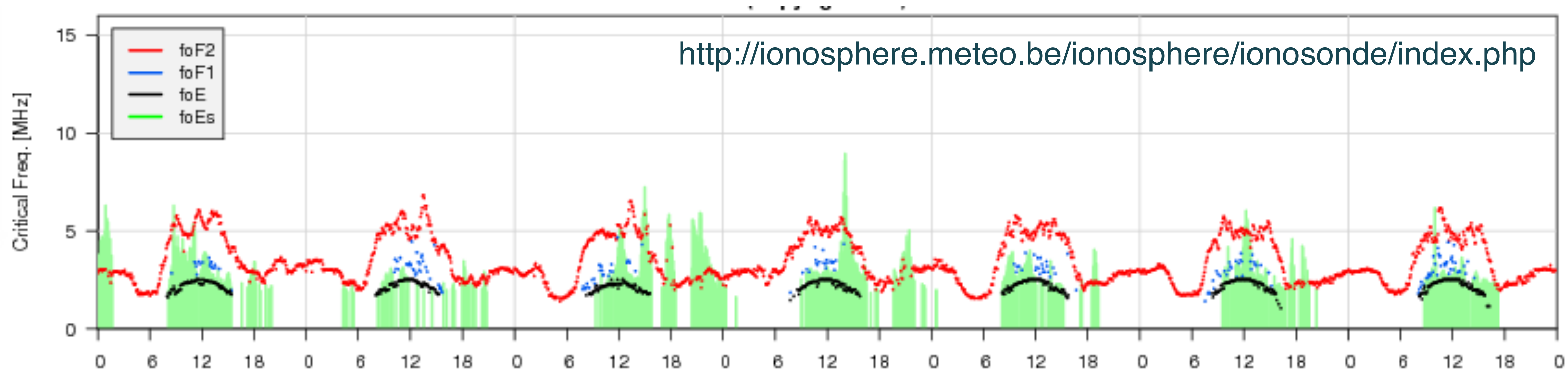
	CUF day	CUF night	Night → Day variation
Spring/autumn	5-6 MHz	2-3 MHz	~ x 2
Summer	5-6 MHz	2-3 MHz	~ x 2
Winter	5-6 MHz	2-3 MHz	~ x 2

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

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

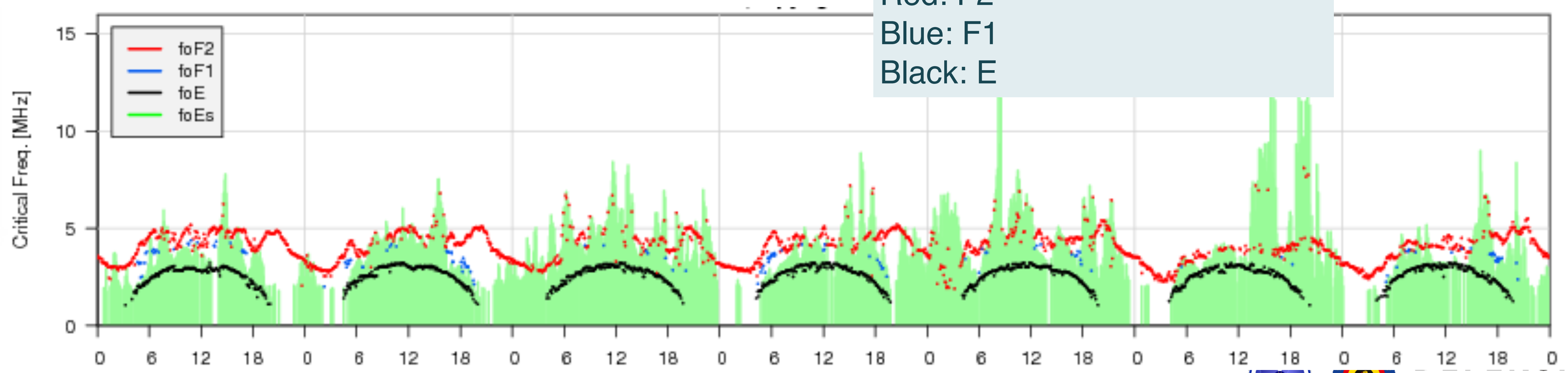
DEFENSIE
LA DÉFENSE

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



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)

Ionosonde at Dourbes (DB049), © RMI

High solar cycle

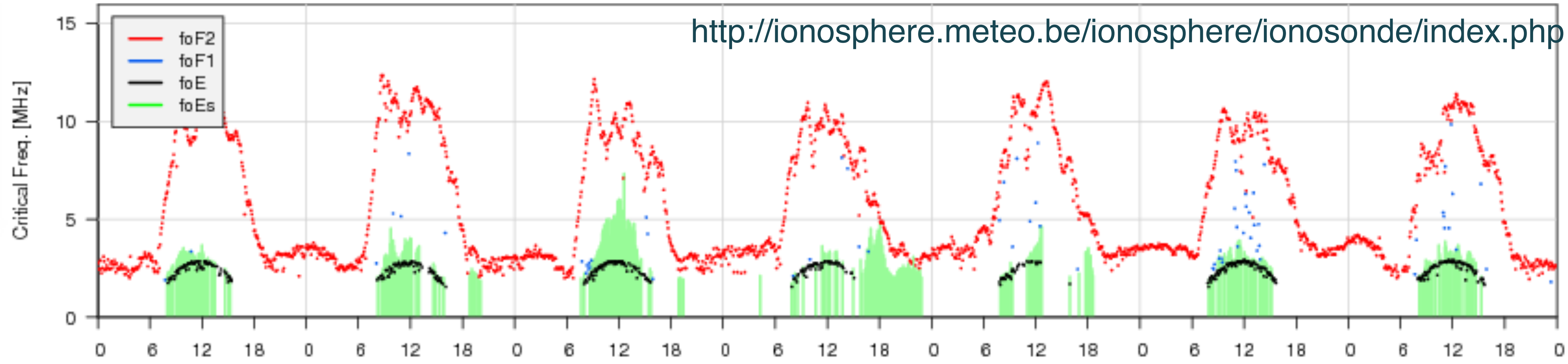
	CUF day	CUF night	Night → Day variation
Spring/autumn	8-10 MHz	5-6 MHz	~ x 1,5 – 2
Summer	6-9 MHz	4-6 MHz	~ x 1 – 1,5
Winter	10-12 MHz	3-4 MHz	~ x 3 – 4

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

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

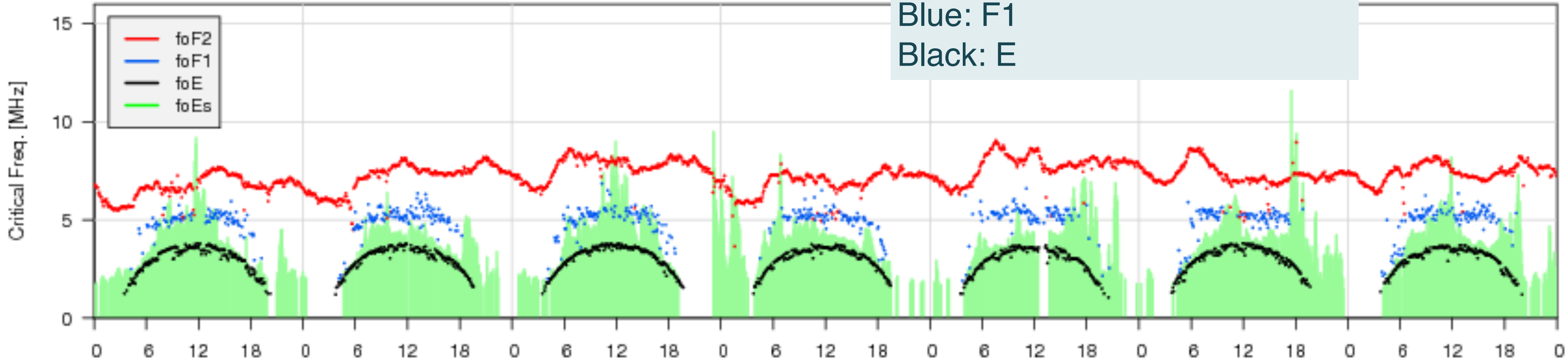
DEFENSIE
LA DÉFENSE

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)

Ionosonde at Dourbes (DB049), © RMI

A few additional reminders…

No link at the poles?
→ Consider using a relay station on a more temperate latitude

HF crossing the poles: extremely unreliable

The Grey Line works miracles for challenging links and long distance links

Want to play around on HF?

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

Ireland Kiwi#1ei6iz

VOACAP Online for Ham Radio

QSO/SWL real time maps and lists

International Beacon Project Azimuthal Map

DEFENSIE
LA DÉFENSE

DEFENSIE
LA DÉFENSE

Q&A