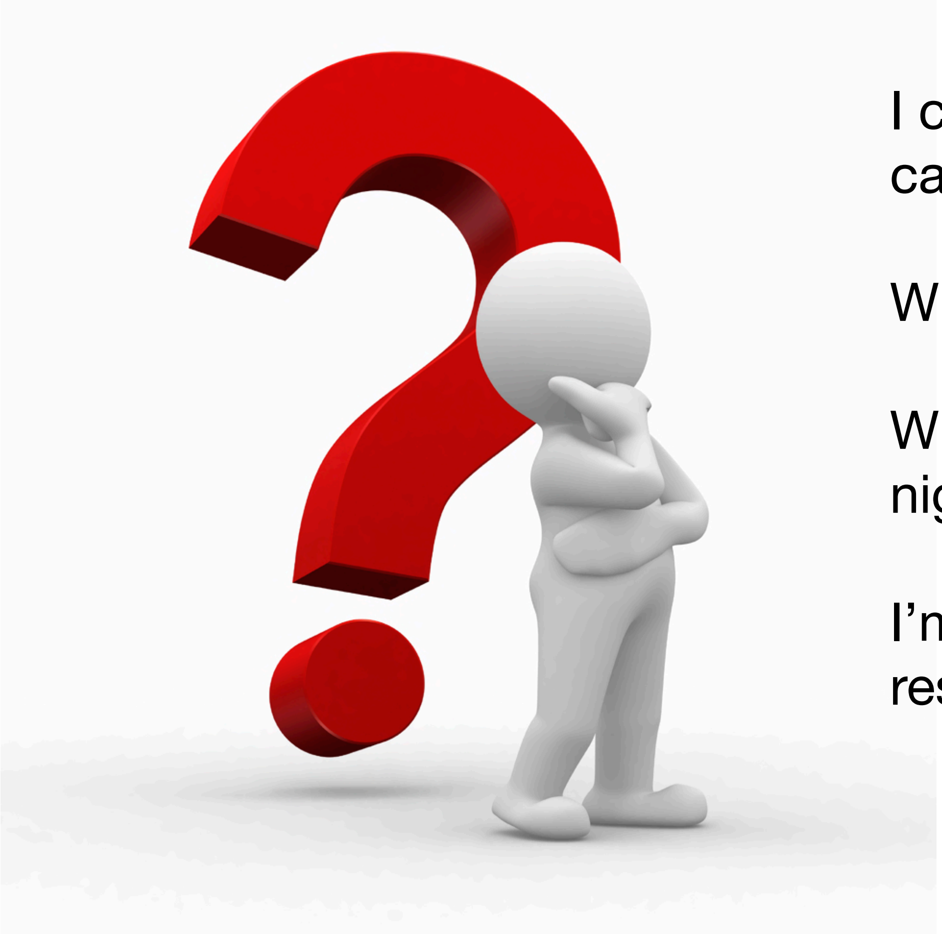
Propagation path analysis on the HF bands using Software Defined Radio and FST4W

HF Propagation - What is going on ?



I can hear Johann on 20m, he’s only 100km away on 20m, but it can’t be ground wave can it ?

Why is my transatlantic signal so strong and stable today ?

Why was there a gap in reception from the Canary Islands last night ?

I’m not decoding VY0ERC very often today, could that be the result of a geomagnetic storm ?

A correctly set up SDR running FST4W can start to answer these questions!

HF Propagation - Ionosphere

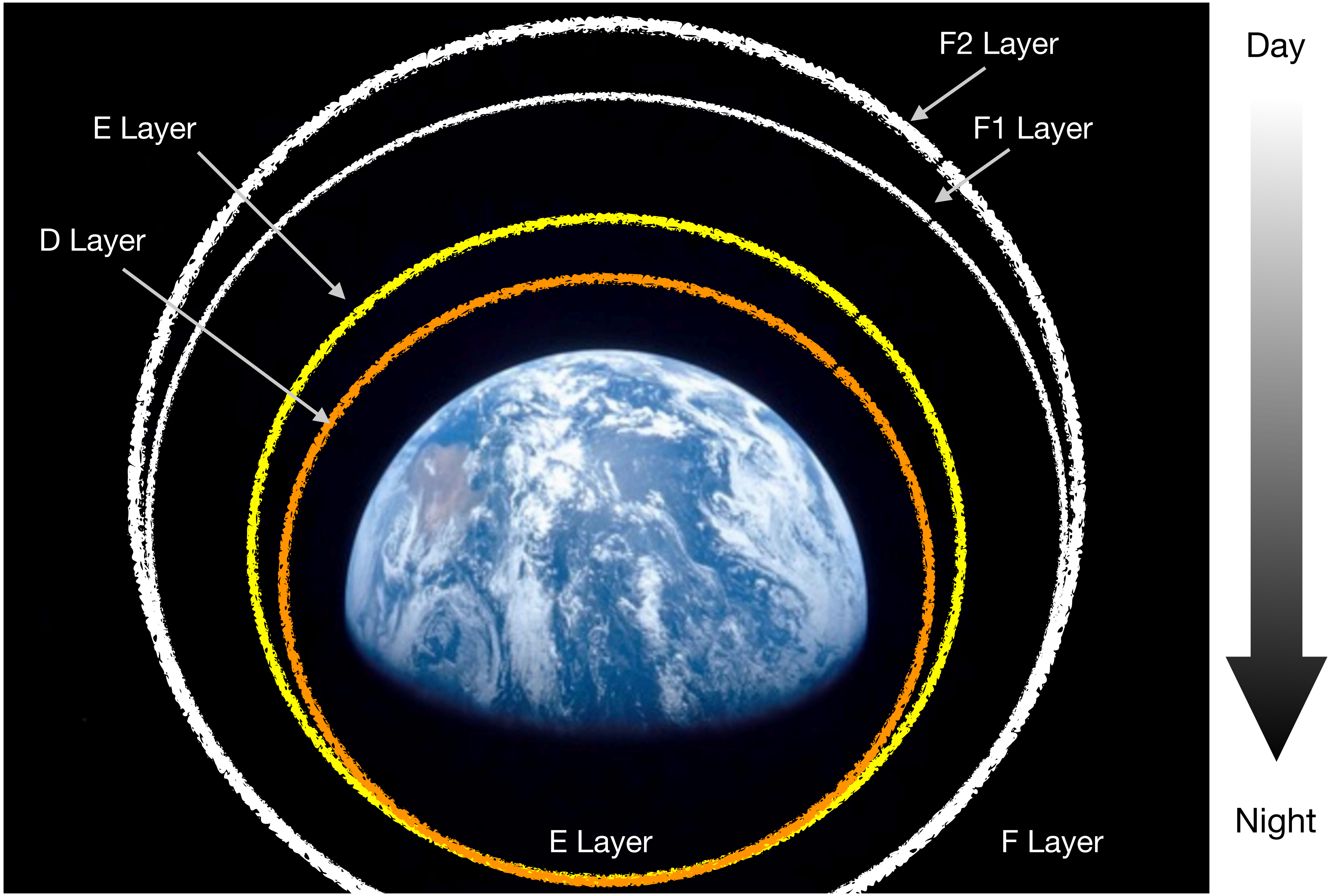
F2 Layer: 300km

F1 Layer: 200km

E Layer: 100km

D Layer: 80km

Approximate
height of peak
electron density

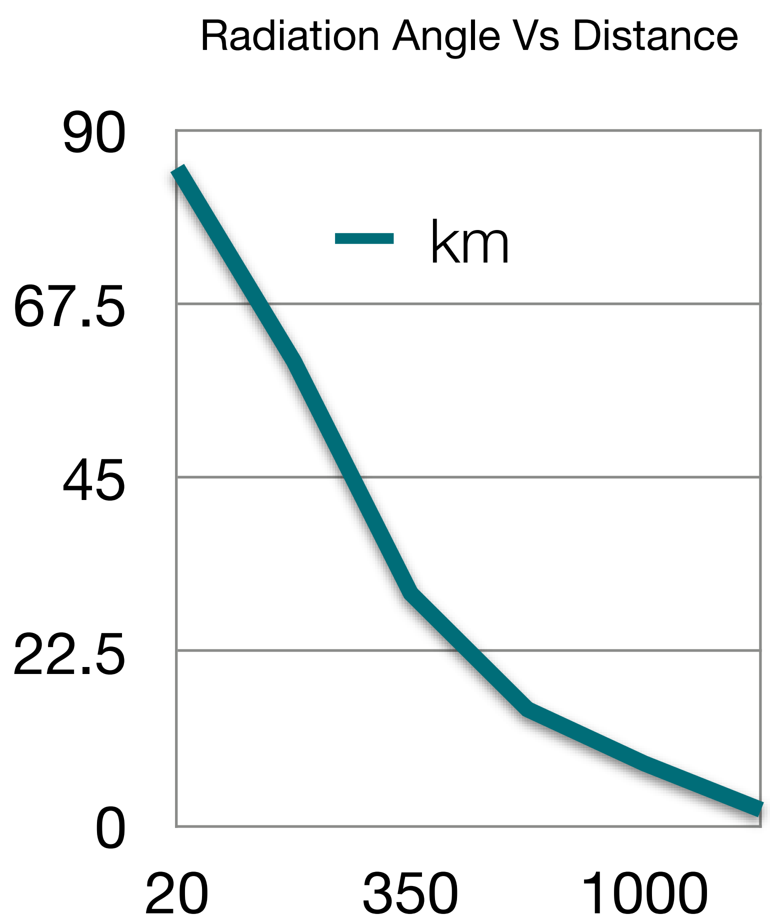


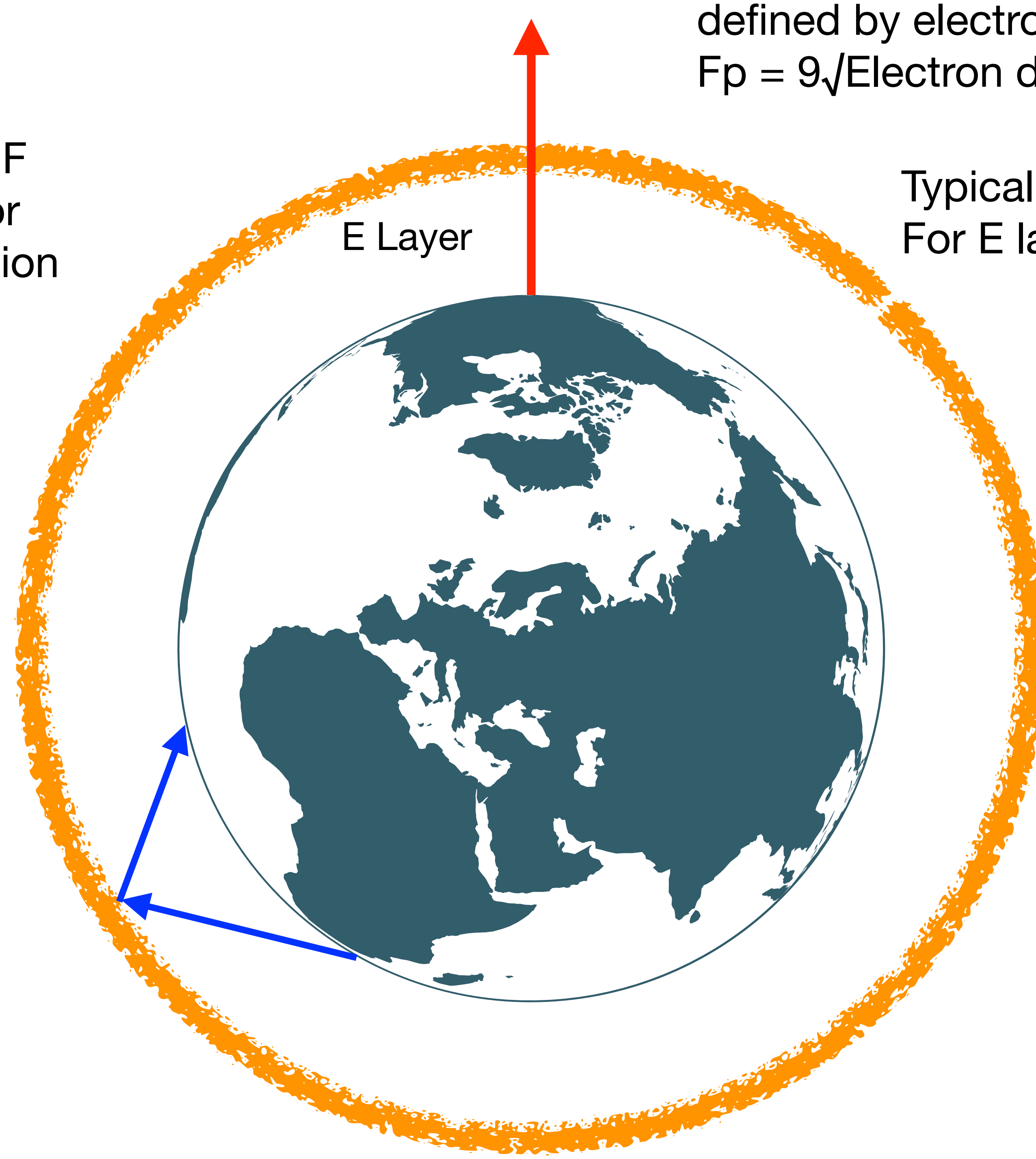
E Layer Maximum Useable Frequency (MUF)

HF pass through layer above critical or "penetration" plasma frequency, Fp, defined by electron density :
$Fp = 9\sqrt{\text{Electron density}}$

At or below critical frequency, HF reflects off the layer. Reflection or Skip distance depends on radiation angle.

Typical critical frequency For E layer = 2.5 - 3 MHz





F Layer Maximum Useable Frequency (MUF)

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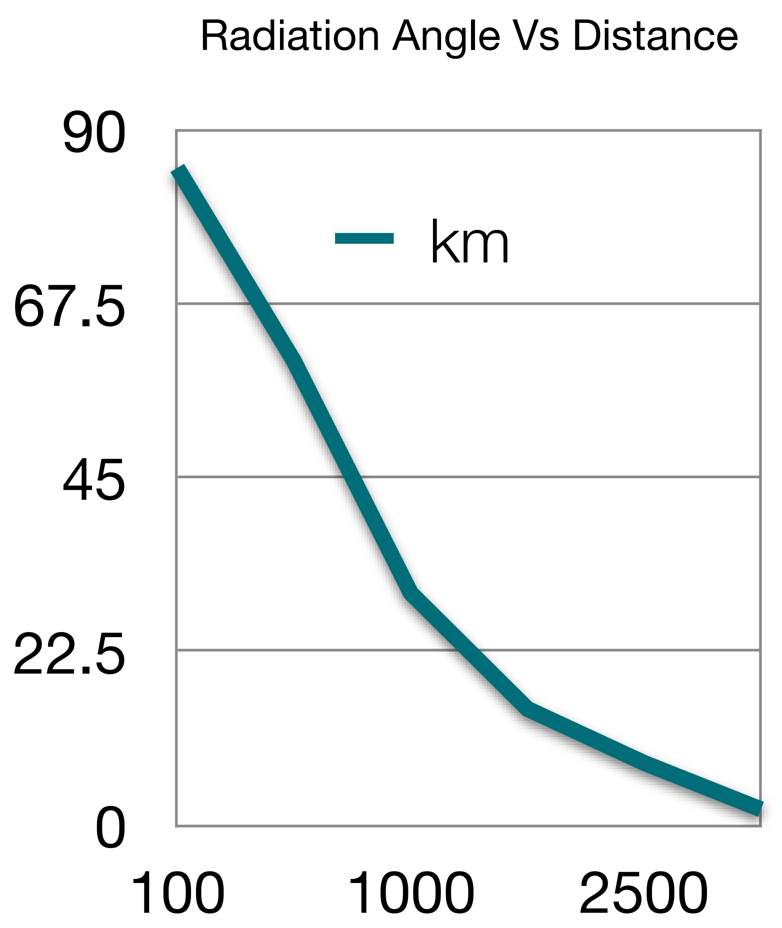
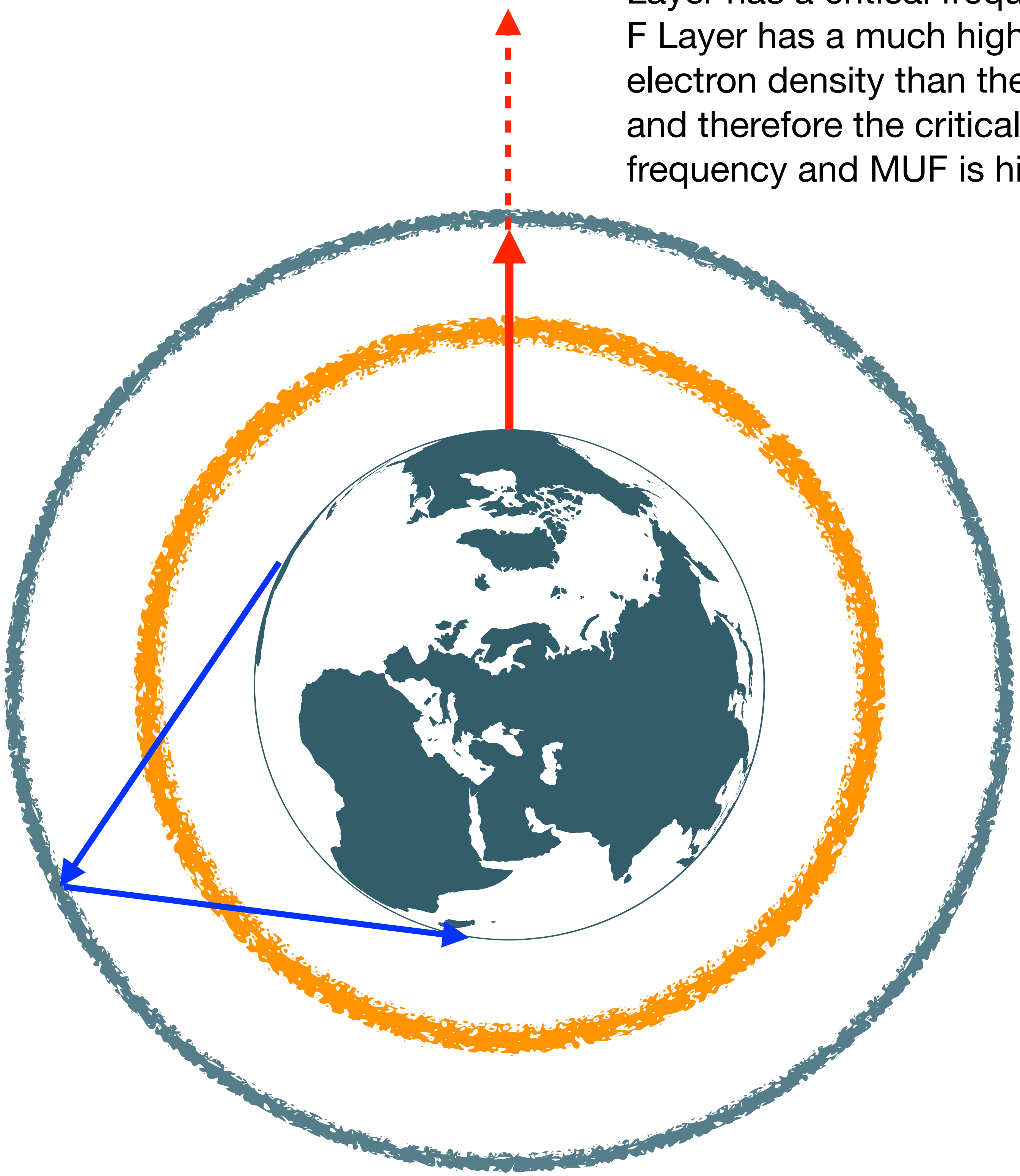


Just as for the E Layer, the F Layer has a critical frequency. The F Layer has a much higher electron density than the E Layer, and therefore the critical frequency and MUF is higher.



The rapidly moving layers

The Ionosphere is changing all the time:

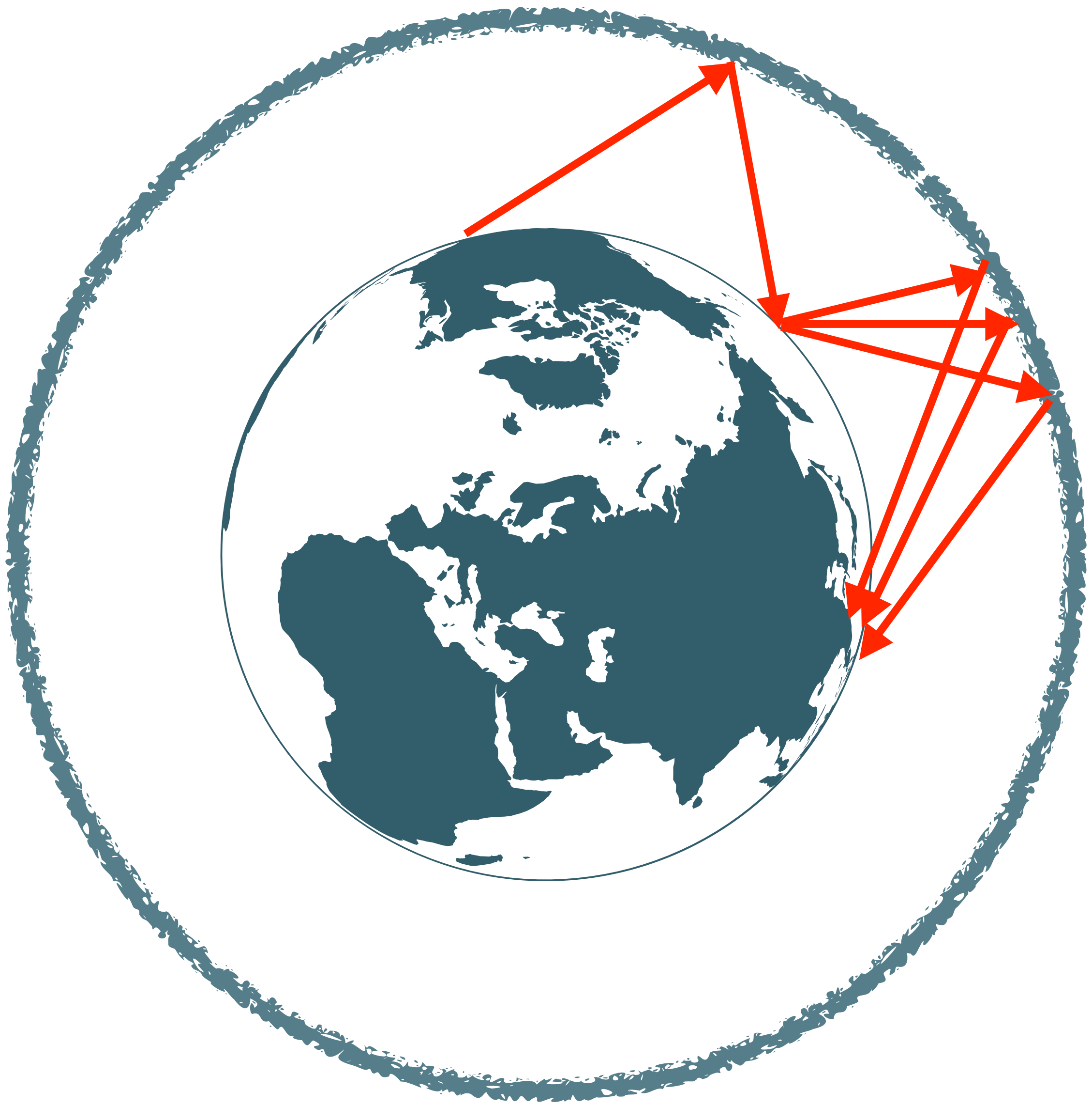
- Layer height changes
- Layer electron density changes
    - Vertical density changes
    - Horizontal density changes

These rapid changes to the layer height or the electron density cause small Doppler Shifts to the received signals. Such shifts may be positive *and* negative, giving rise to :

Spectral Spread

Layer	Characteristics
F2	Layer has much higher electron density than E Layer, resulting in much higher MUF. Generally less predictable than E layer.
F1	F1 Layer splits from the F2 Layer during the hours of daylight, and extends from the top of the E layer to the bottom of the F2 layer. Electron density is low, resulting in HF penetration.
E	Layer is influenced by solar radiation (day/night) and sunspots. Typical E Layer MUF is low HF : 2.5 to 3MHz, but sporadic E can be influence much higher frequencies
D	D layer ionisation is controlled by solar radiation, peaks around midday and disappears at night. Layer absorbs low frequencies and is main factor in Lowest usable Frequency (LUF). Important at MF and LF.

Spectral Spread



There are two significant causes of spectral spread:

1. Ionospheric - positive and negative doppler shifts caused by rapid changes in layer height and / or electron density.

2. Multipath spectral spread: A 2nd hop on a path involves reflection from the ground or ocean, which will produce multiple reflections at different angles, and these will be reflected in different parts of the ionosphere on the 2nd hop, causing more spreading.

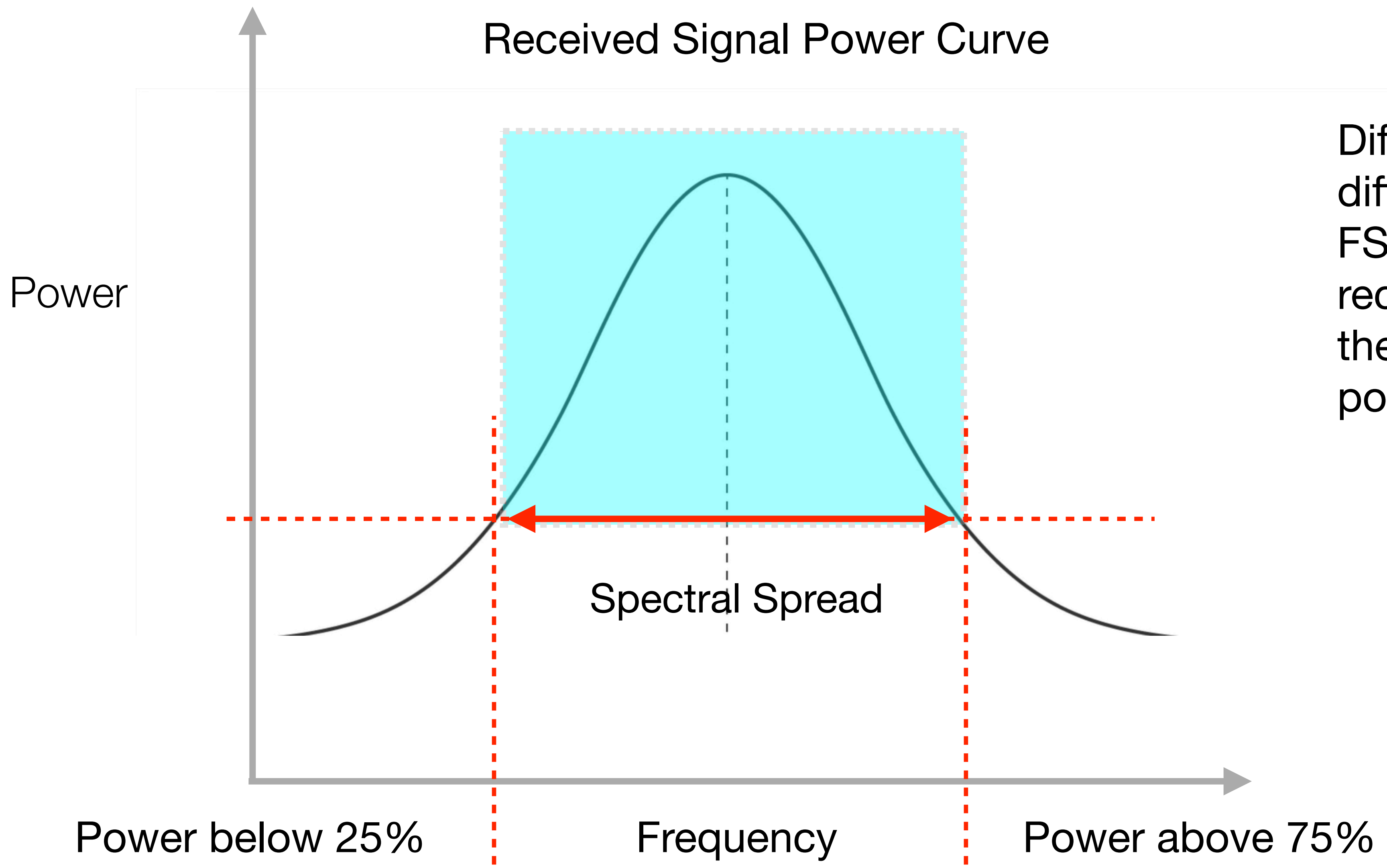
Propagation Research using Spectral Spread

By using spectral spread measurements, together with s/n ratios we can distinguish between:

- Ground wave / sky wave propagation
- Single hop
- Multihop with ground reflection
- Multihop intra - ionosphere layer propagation (ducting)
- Single ? and multi hop backscatter / side scatter

But, there are some technical challenges along the way

Measuring Spectral Spread



Different papers on the subject use different definitions. We use the FST4W calculation of 50% of the received signal power, lying between the 25% and 75% points on the power curve.

Do all HF signals have spectral spread ?

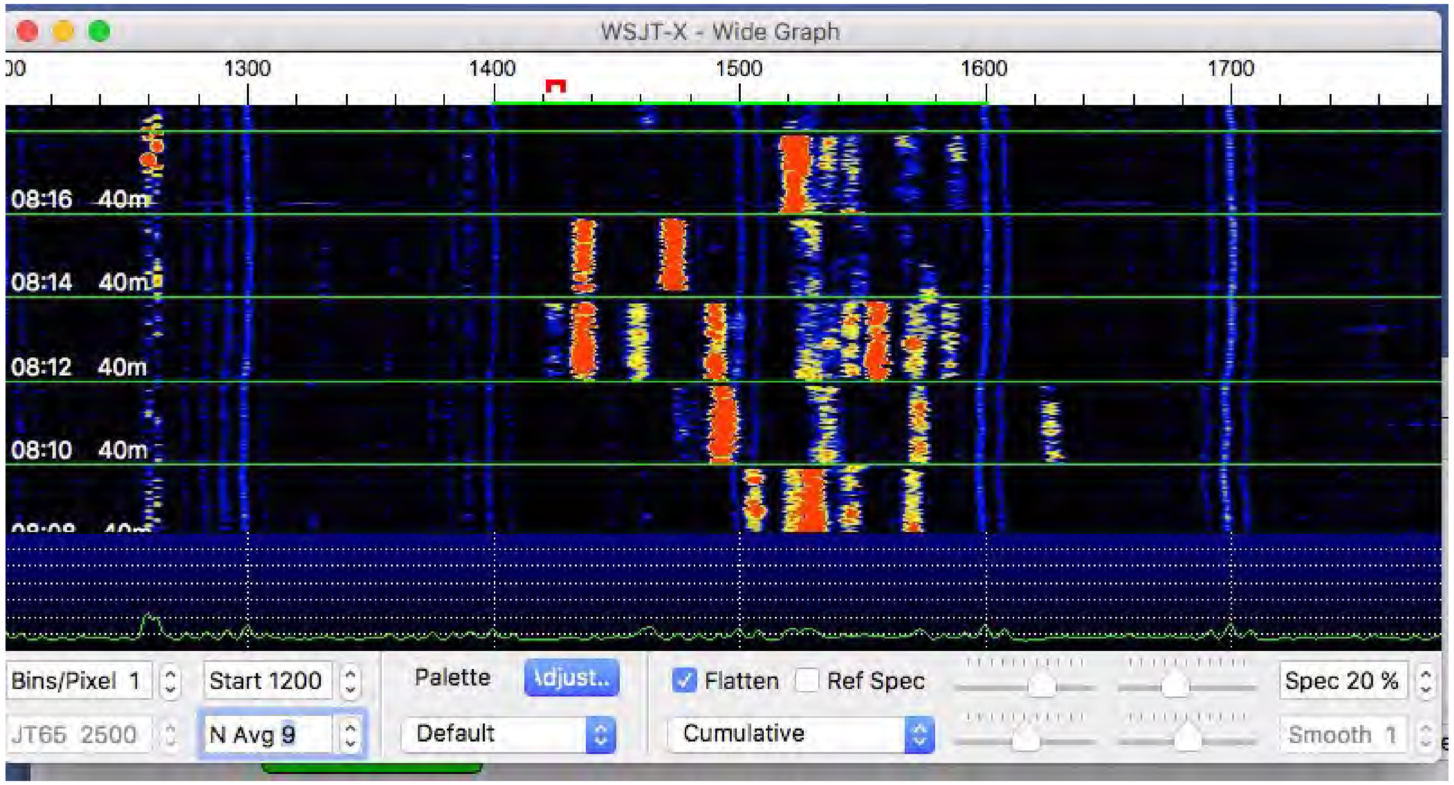
Yes - unless they are received via ground wave.

But…. Ionospheric spreading is in the order of tens or hundreds of ***millihertz***. If we want to look at this effect in the HF bands we need equipment with stability that is significantly better than current free standing oscillators, as well as a way of measuring millihertz received spectrum spread

Source	Stability at 14MHz
VFO	+/- 120 Hz
Ordinary XO	+/- 42 Hz
Icom-IC7300	+/- 7Hz
TCXO	+/- 1.4 Hz

* Table thanks to WB6CXC

FST4W Digital Mode used for HF Propagation research



WSPR is an extremely well known tool with many uses such as antenna research and finding current propagation conditions. Over some years a huge amount of data has been gathered over many bands.

However, the WSPR protocol and decoding software is designed to work with current Ham transceivers, and despite its narrow 6Hz bandwidth, it can accept tx or rx frequency drift of 4Hz or so.

WSPR is unsuitable for research involving millihertz spectral spread

- FST4W is a beaconing mode similar to WSPR, but designed specifically for 2200m (136KHz) and 630m (472KHz) operation.
- At these frequencies, modern Ham equipment stability (+/-0.5ppm) only has a drift of +/- 60 mHz at 2200m and +/- 230mHz at 630m.

FST4W software computes spectral spread

You think 6Hz WSPR is Narrowband ?

FST4W has four modes - in which it actually sends exactly the same data, just more slowly. The threshold SNR is the SNR at which the probability of a decode drops below 0.5, but only for very low spreading (10 mHz

Parameter	FST4W-120	FST4W-300	FST4W-900	FST4W-1800
SNR threshold (dB)	-32.8	-36.8	-41.7	-44.8
Symbol length (s)	0.683	1.792	5.547	11.2
Tone spacing (Hz)	1.46	0.56	0.18	0.089
Occupied bandwidth (Hz)	5.9	2.2	0.74	0.36
Measured Spectral Width (Hz)	5.3	2.14	0.72	0.35

The slower you go, the less the bandwidth and better the S/N threshold

FST4W Quick Start Guide : “achieving the sensitivities listed in the table requires that oscillator drifts and path-induced Doppler shifts must be less than the tone spacing, over the full sequence length”

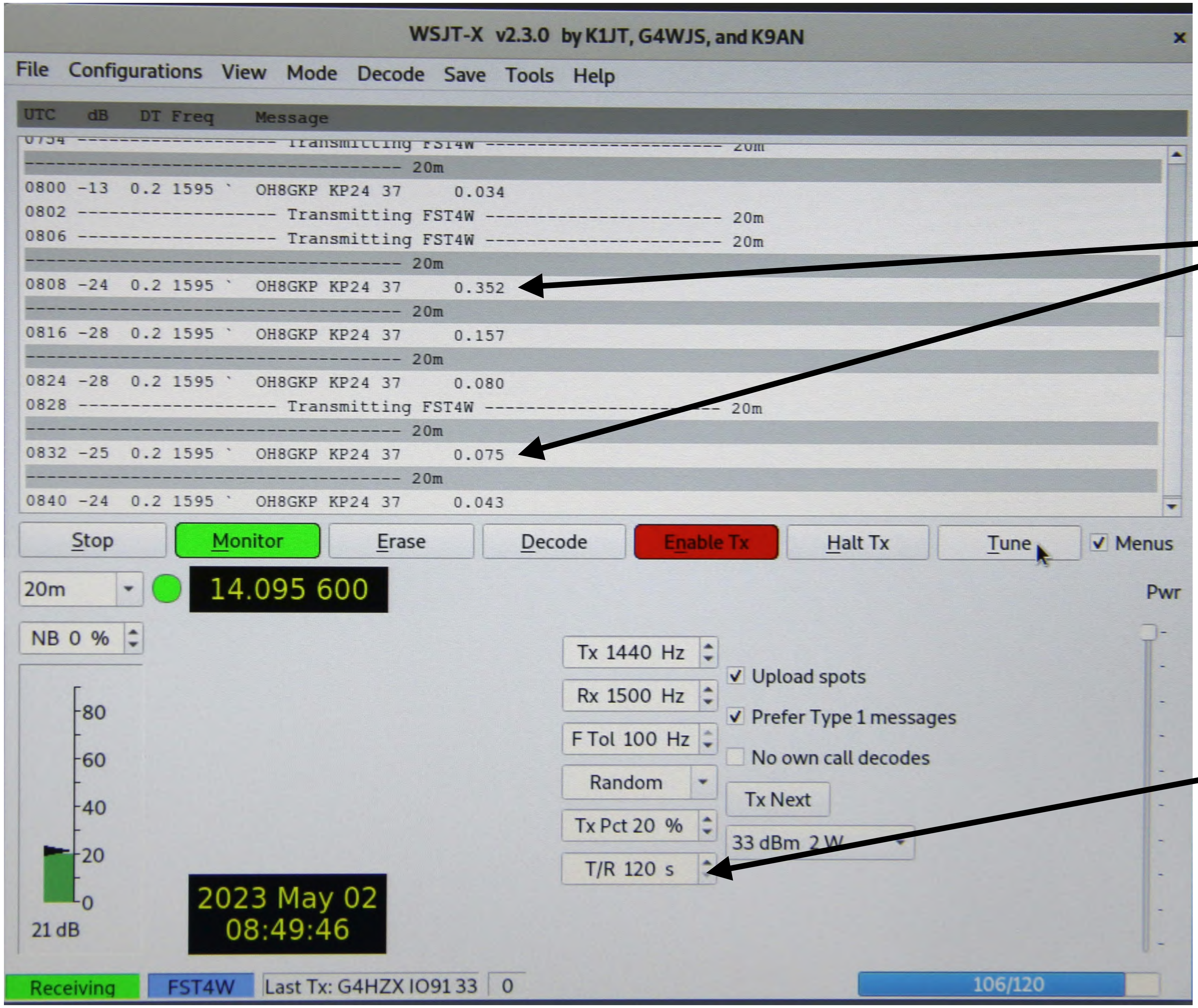
Digital Mode Signal to Noise

Signal to Noise ratios (SNR) as reported by WSJTX and WSPRDaemon are normalised to the standard 2500Hz SSB bandwidth. This gives a false impression of the ability of these modes to decode signals below the noise. The reality is impressive, but not quite the same : FST4W (and WSPR) can ***NOT*** decode signals l000 times weaker (-30dB) than the noise!

Adjusting for bandwidth is simple, correction = 10Log10 (bandwidth1/bandwidth2)

Mode	Threshold S/N 2.5KHz	Threshold S/N in channel
FST4W-120	-32.8 dB	-6.1 dB
FST4W-300	-36.8 dB	-6.1 dB
FST4W-900	-41.7 dB	-6.2 dB
FST4W-1200	-44.8 dB	-6.2 dB

WSJTX Spectral Spread Output



Spectral Spread in Hz

FST4W Mode - in this case FST4W-120

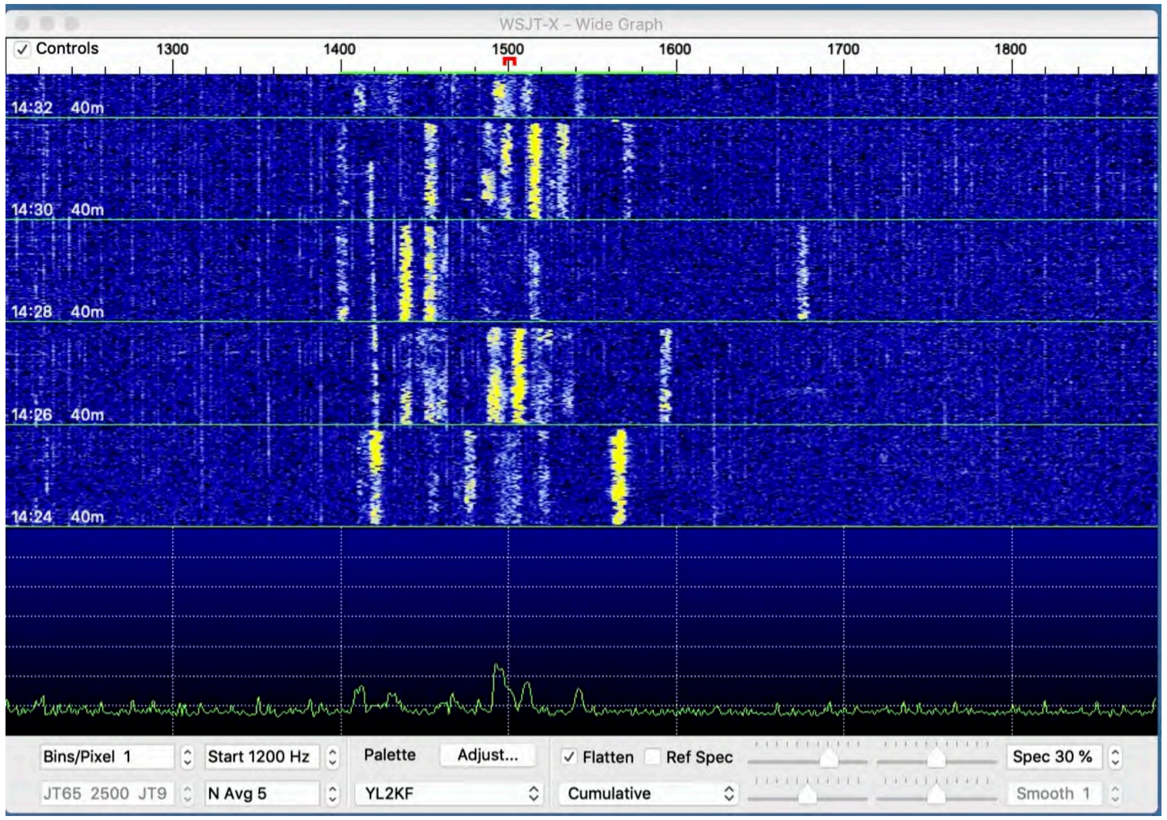
Extending use of FST4W to the HF bands

WSPR and other digital modes have revealed that statistically reliable communication is possible over paths which we used to think impossible

We now have a massive database of spots which can be linked to time, solar activity and ionospheric disturbances

But we don't know:

- **The RF path**
- **The number of hops**
- **The propagation mechanism**



Spectral Spread information derived from FST4W allows us to add more Information to start to understand this.

Where does SDR fit in ?

This very low cost ($69 in kit form) high performance digital mode transceiver is an ideal platform for FST4W transmission and reception. LF version is 80-40-30-20m, HF version 20-17-15-12-11-10m

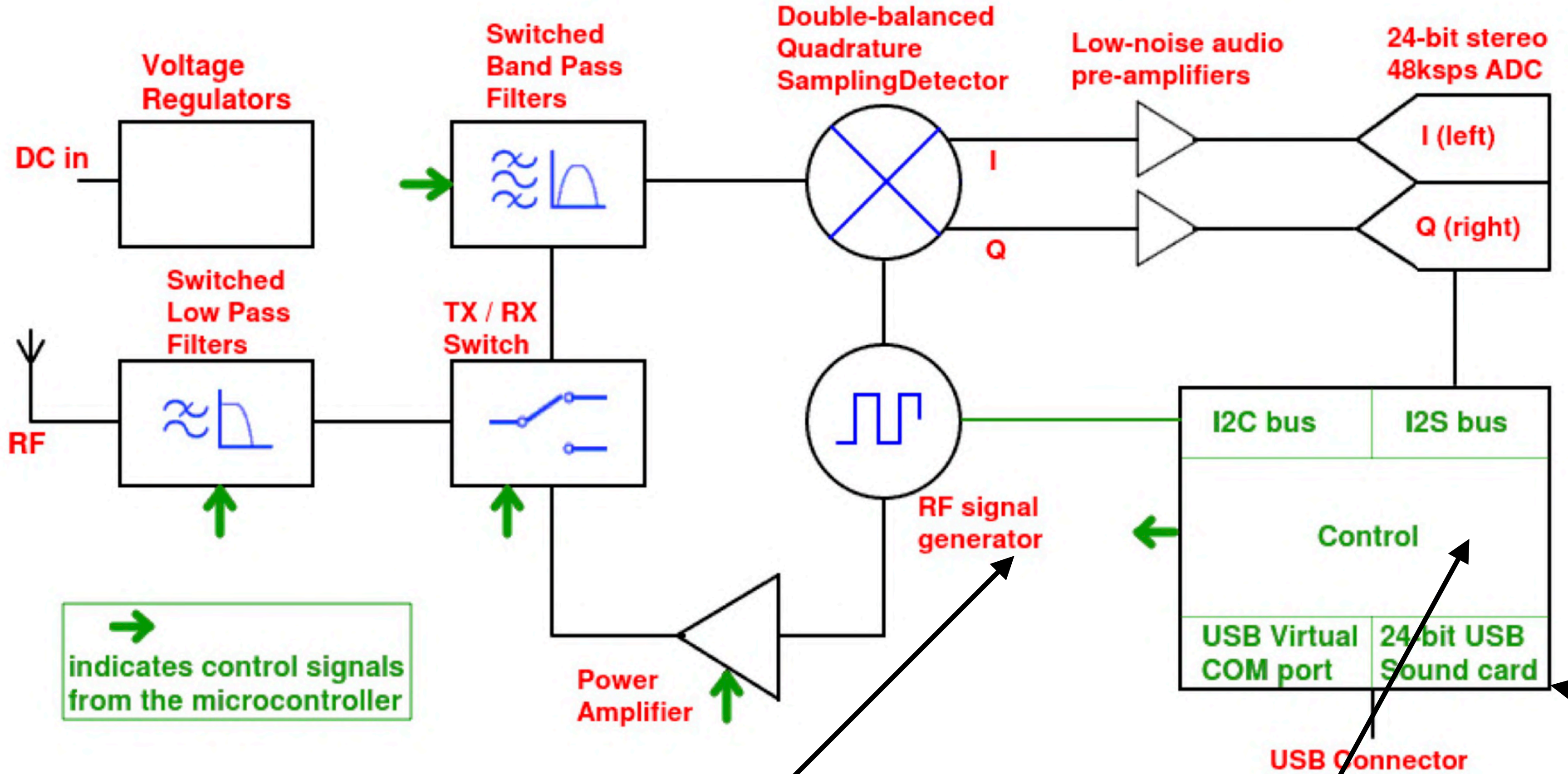
RX :

- Superhet with 12KHz IF, completely implemented in onboard software
- Integral sound card emulation with high dynamic range
- TCXO for high stability

TX:

- FSK modes only
- FSK implemented by changing directly synthesised tx frequency from input digital audio
- Exceptionally clean output
- Up to 5w output

QRP Labs QDX Transceiver



Sound card is Software implementation

Frequency of PLL synthesised RF generator *digitally* shifted by incoming tone from PC.

SDR Superhet implemented in firmware in control processor

QDX and Stability

FST4W Quick Start Guide : “achieving the sensitivities …. requires that oscillator drifts and path-induced Doppler shifts must be less than the tone spacing, over the full sequence length”

The QDX Onboard TCXO is very good (most are better than this table, typical is around 0.25Hz) , but if we require full sensitivity, then the factory QDX is really only useful on 14MHz or lower.
Also, this local drift obscures millihertz ionospheric doppler spreading

QDX worst case stability & FST4W Requirements

Band	Stability +/-	FST4W-120 tone spacing	FST4W-300 tone spacing
80m	0.35	1.46	0.56
40m	0.7	1.46	0.56
30m	1.0	1.46	0.56
20m	1.4	1.46	0.56
17m	1.8	1.46	0.56
15m	2.1	1.46	0.56
12m	2.4	1.46	0.56
10m	2.8	1.46	0.56

GPS to the Rescue!

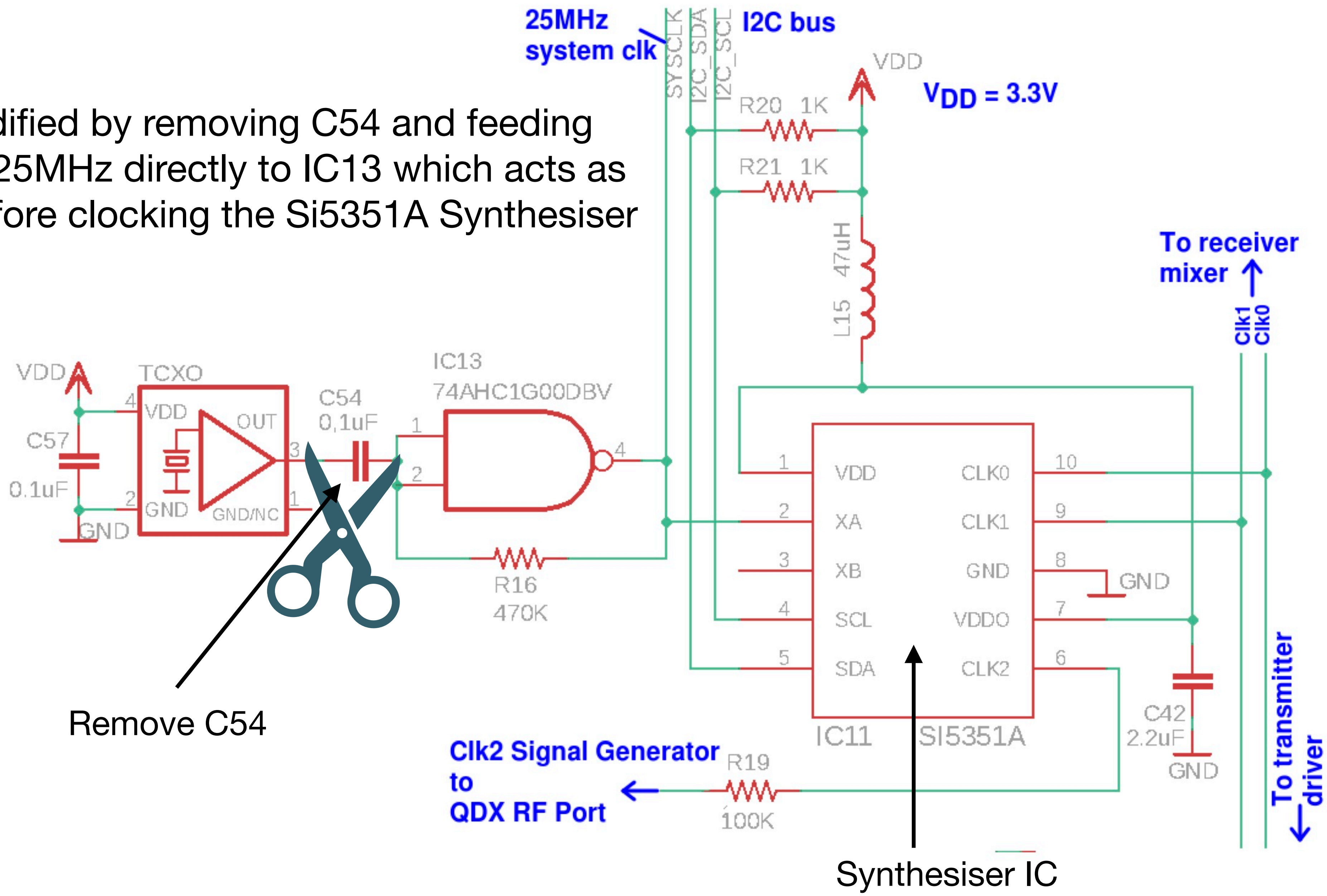
Affordable GPS Disciplined Oscillators (GPSDO) are now available.
They provide comparable frequency accuracy and stability to a caesium source for less than €150
Typical short term stability is +/- 0.000001 ppm!

GPSDO Stabilised QDX & FST4W Requirements

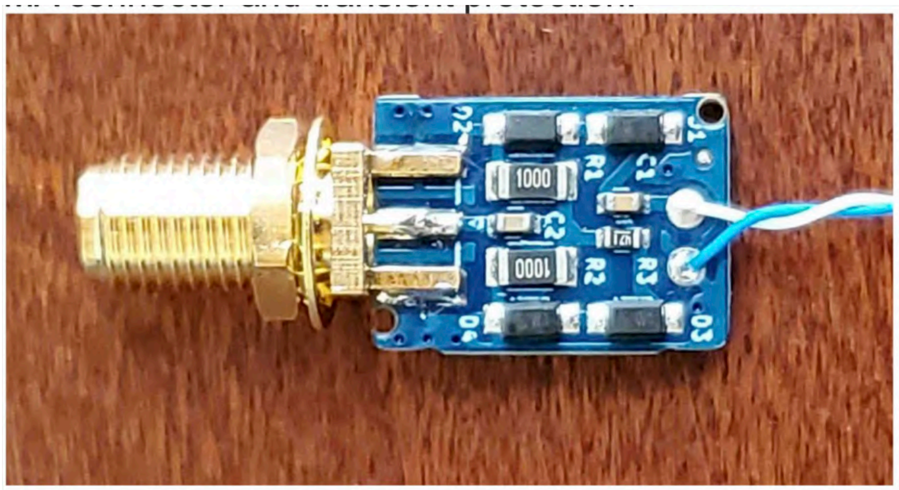
Band	Stability +/-	FST4W-120 tone spacing	FST4W-300 tone spacing	FST4W-900 tone spacing	FST4W-1200 tone spacing
80m	0.000035	1.46	0.56	0.18	0.089
40m	0.00007	1.46	0.56	0.18	0.089
30m	0.0001	1.46	0.56	0.18	0.089
20m	0.00014	1.46	0.56	0.18	0.089
17m	0.00018	1.46	0.56	0.18	0.089
15m	0.00021	1.46	0.56	0.18	0.089
12m	0.00024	1.46	0.56	0.18	0.089
10m	0.00028	1.46	0.56	0.18	0.089

QDX Oscillator Circuit Modification

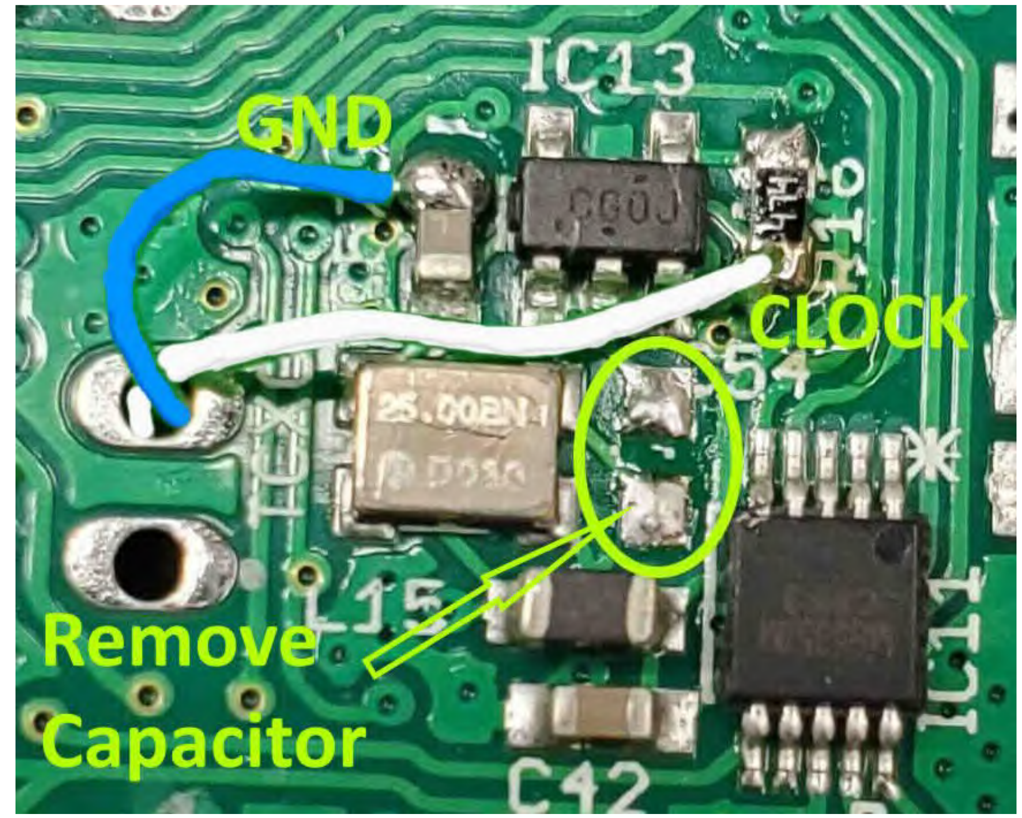
QDX is modified by removing C54 and feeding GPSDO at 25MHz directly to IC13 which acts as A buffer before clocking the Si5351A Synthesiser



QDX Oscillator Circuit Modification



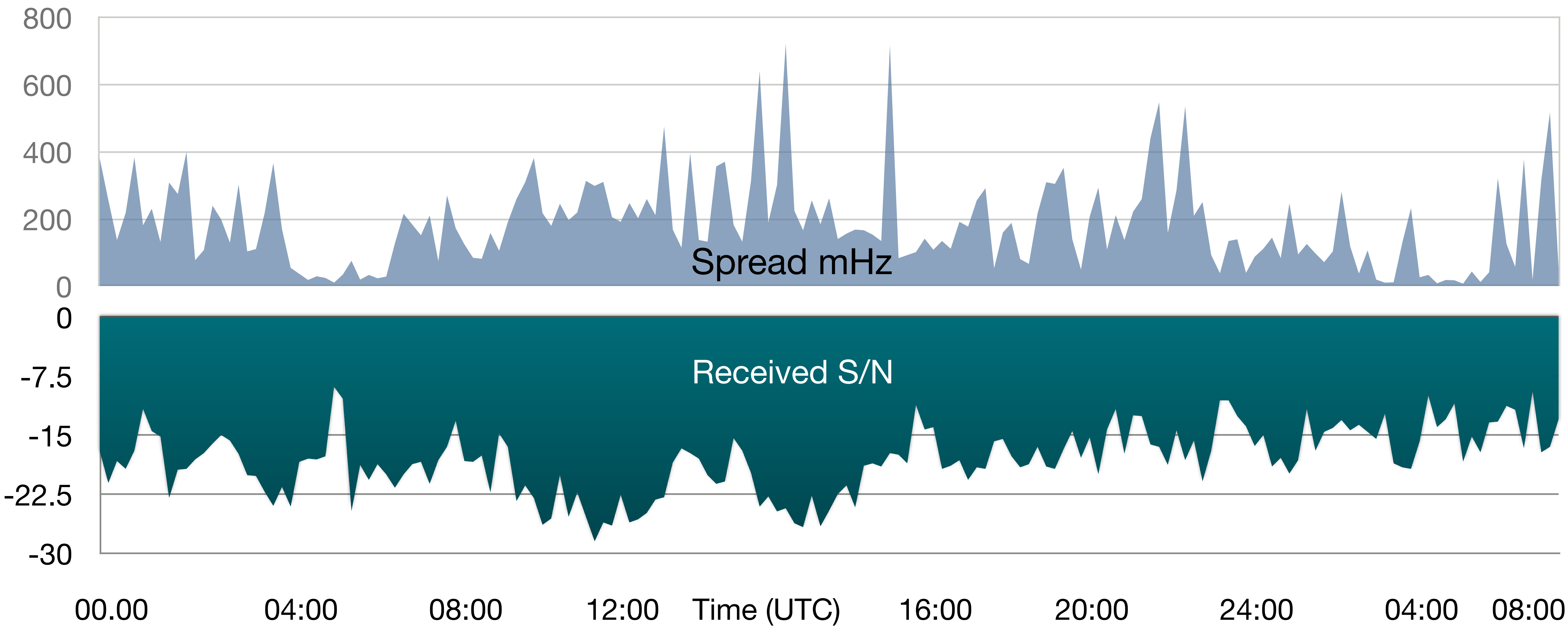
External 25MHz clock interface
board. from WB6CXC
https://turnislandsystem.com



Good eyesight and a steady hand helps!

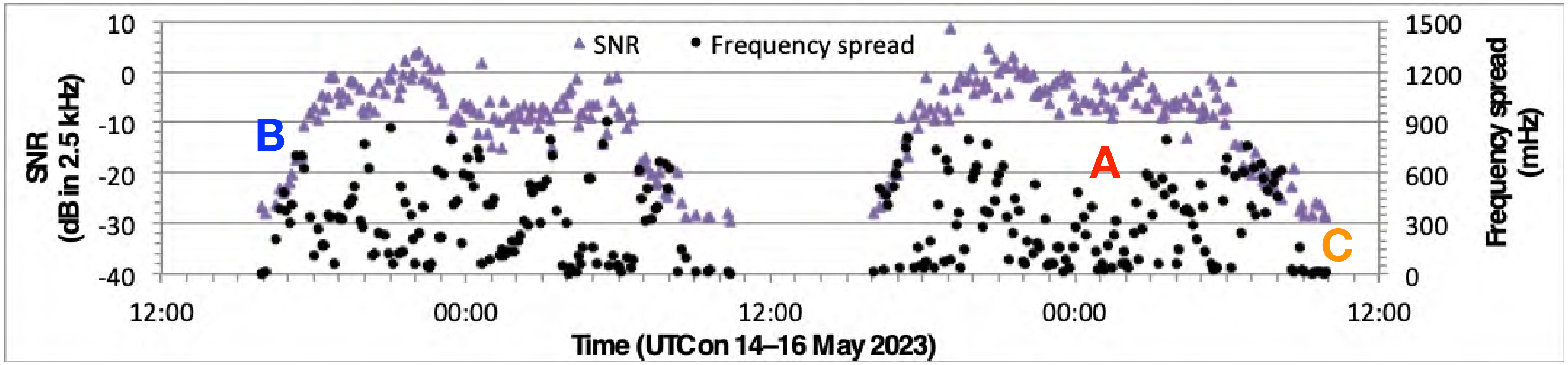
Practical Results

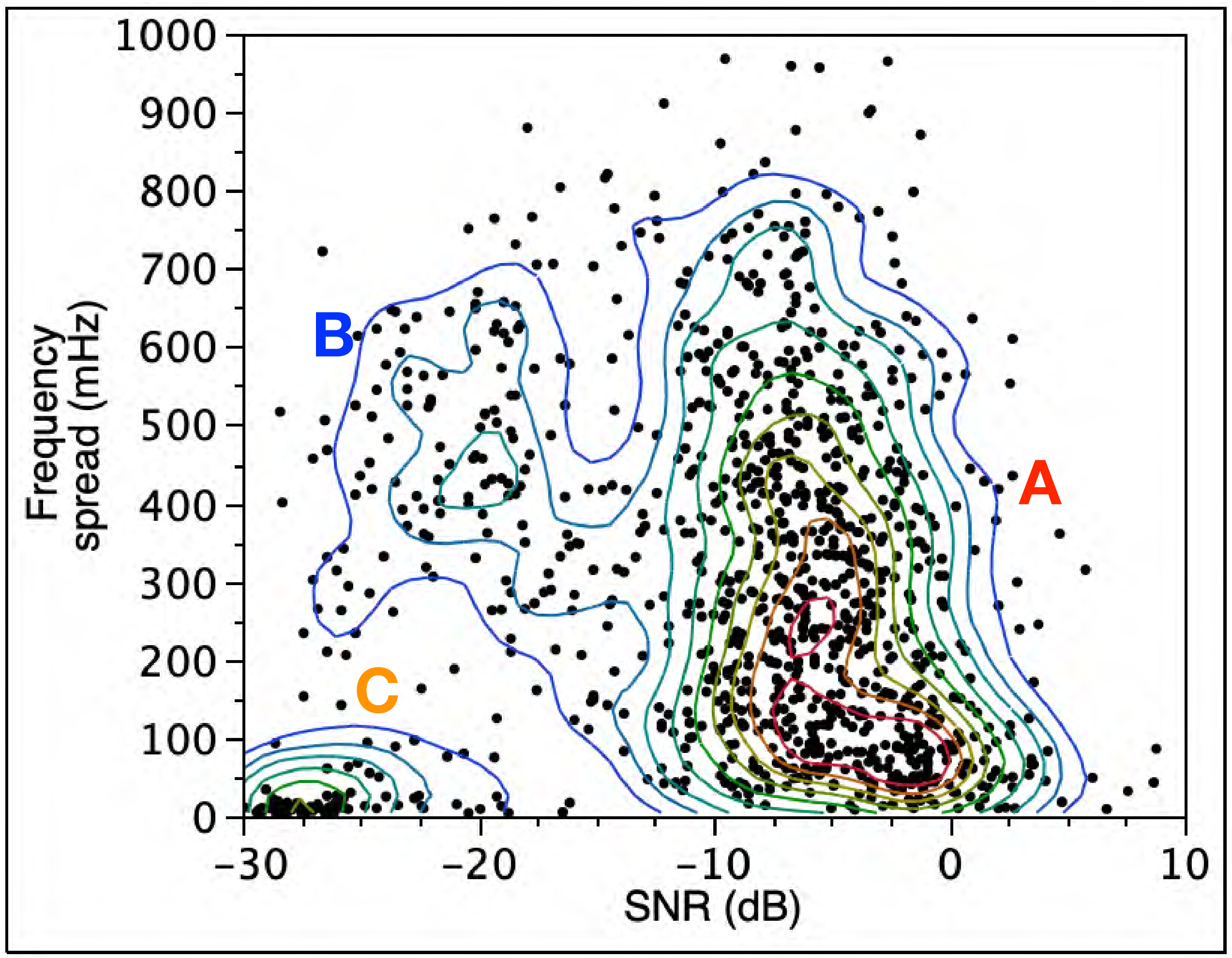
WSJTX is not the only way to access Spectral Spread data, the popular Kiwi SDR receiver can be used with WsprDaemon to collect it - at present in a much more organised way than with WSJTX.   This enables us to build up data sets of time vs Spread and S/N



G4HZX to EA8/DF4UE 14 Mhz 2784 km GPSDO each end 25-26 May 2023

G3ZIL to EA8BFK 7 MHz 2700 km GPSDO each end





Spread and SNR

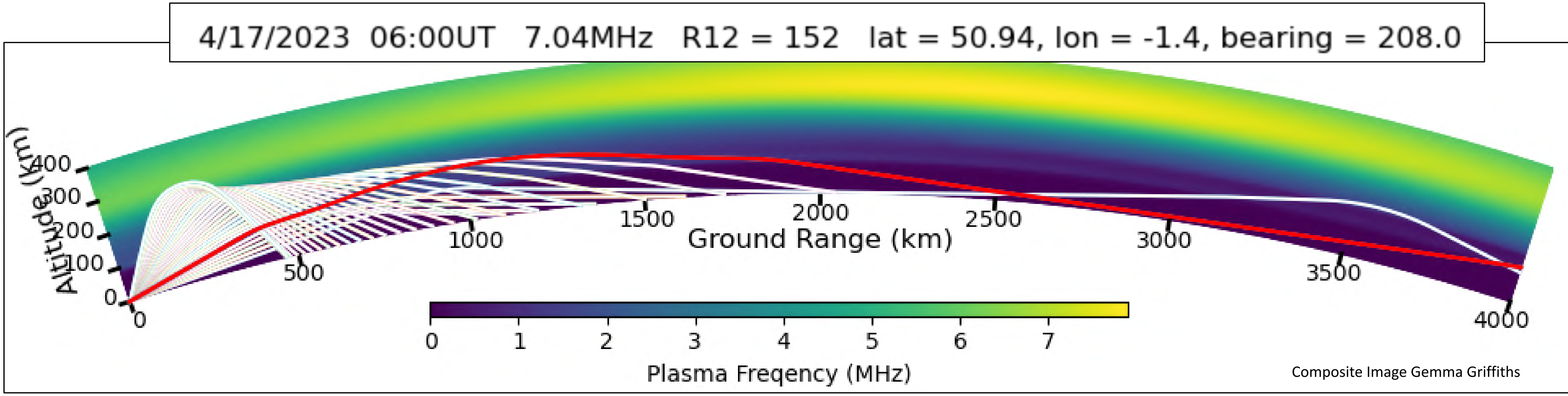
A = band open, mix of 1 to 4 hop propagation throughout the night.

B = band opens or closes, side scatter mode ?

C = single hop, Pedersen Ray ?

G3ZIL to EA8BFK 7 MHz 2700 km GPSDO each end

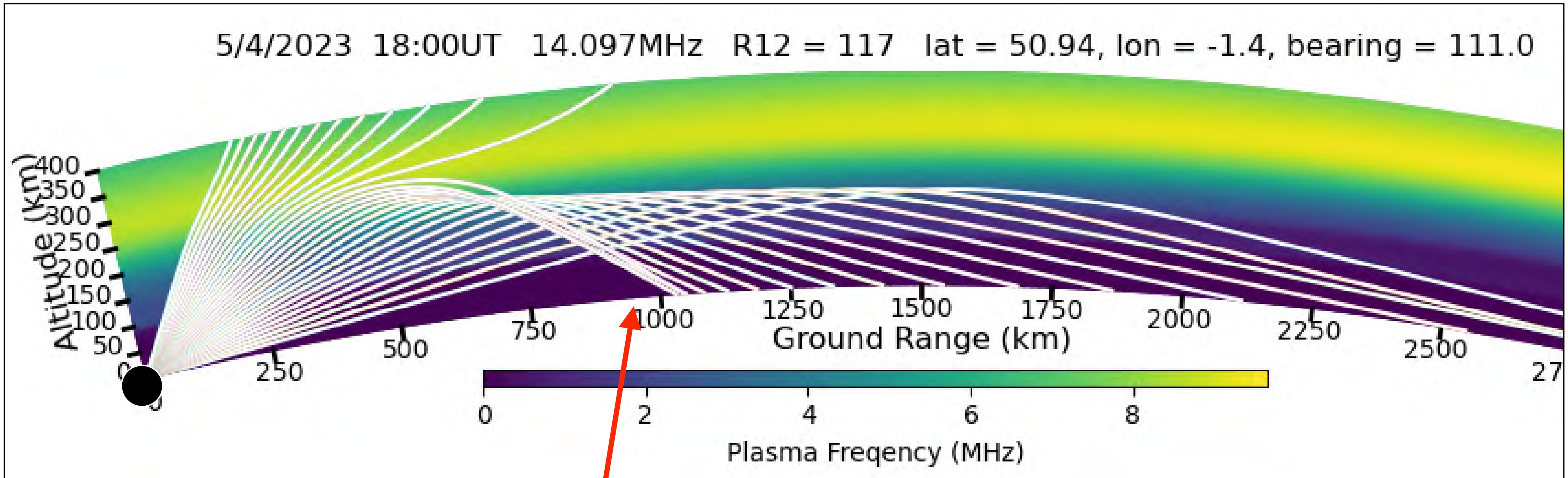
From PyLap Ray Tracing :



Red Ray is possible Pedersen Ray, where ray changes incident angle by multiple refractions in the upper E layer

- Very low spectral spread
- Lossy path. (Low SNR)
- Occurs when band opens and closes

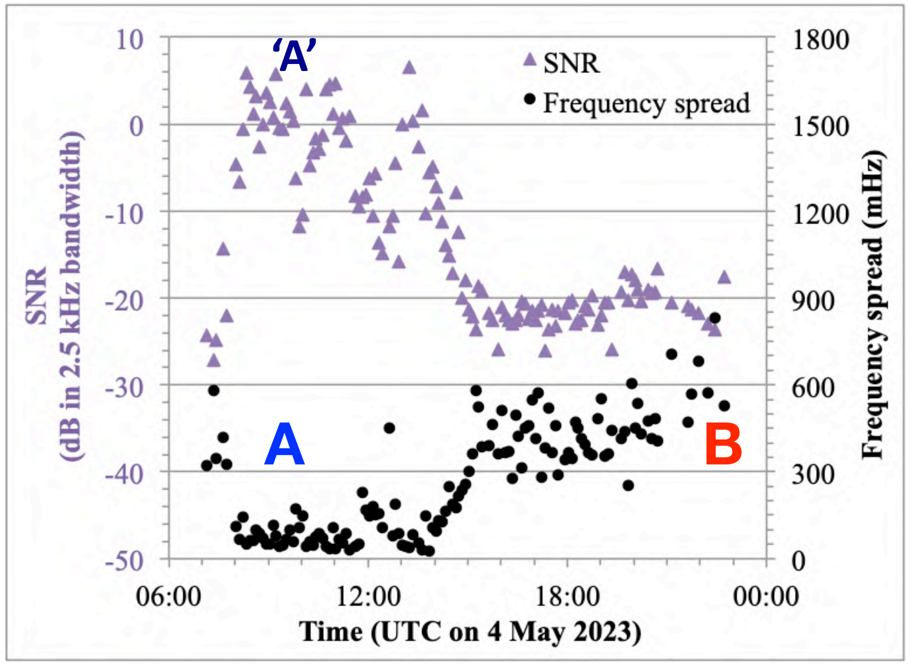
2 Hop Side-Scatter G3ZIL to OE9GHV 900 km on 14 MHz



Dead Zone at 900 Km

Pylap plot suggest that conventional single hop propagation - reflection from F2 layer isn't possible at this time of day. But FST4W signals are received, what is going on ?

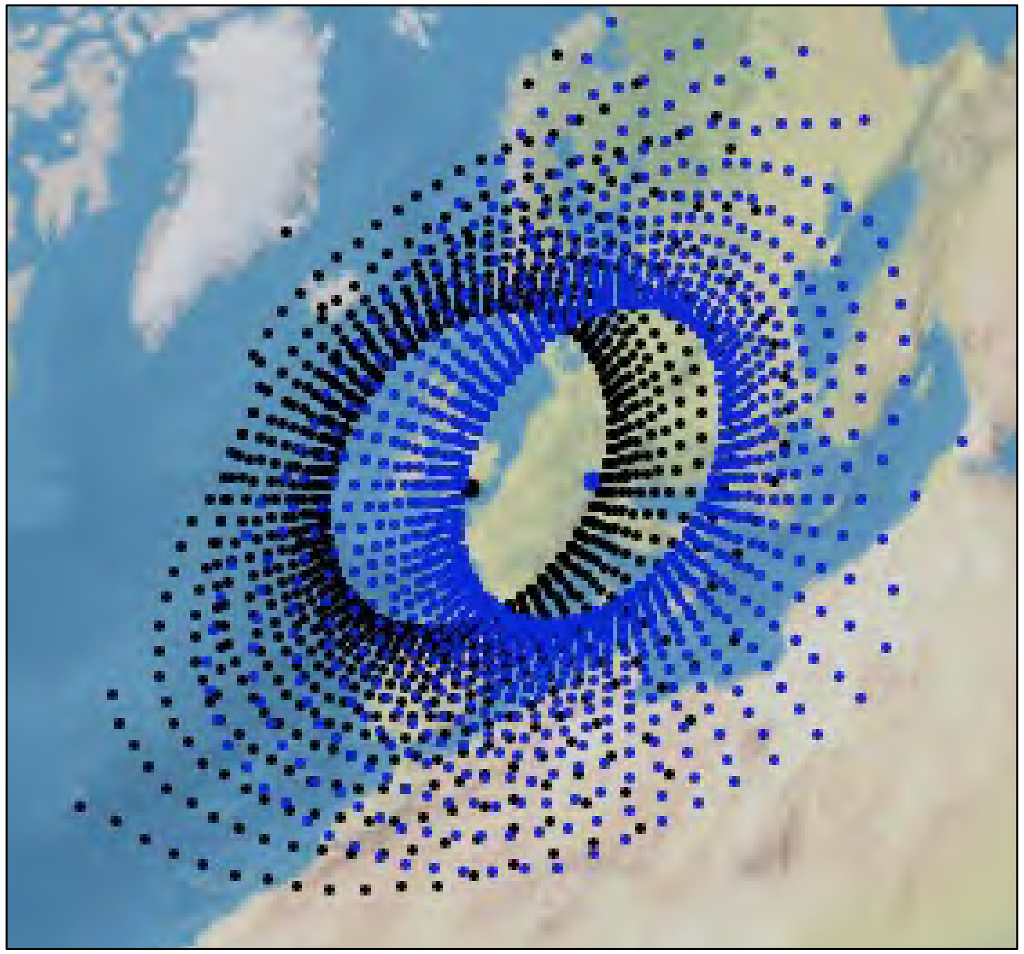
2 Hop Side-Scatter G3ZIL to OE9GHV 900 km on 14 MHz



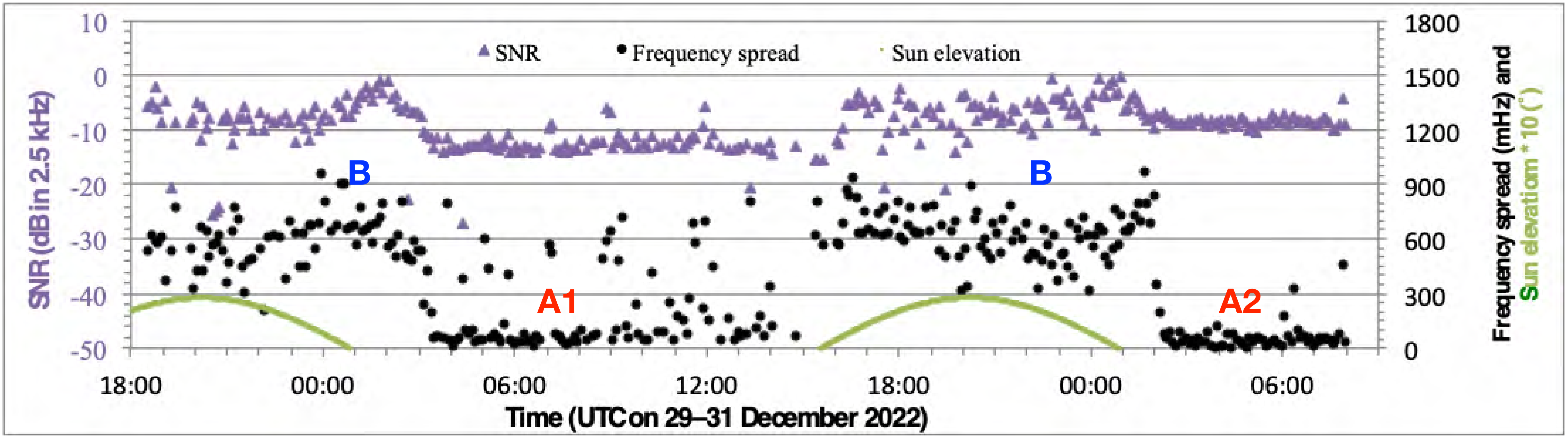
- The low spectral spread at **A** with a high SNR suggests a standard single hop
- But the lower SNR and high spread at **B** suggest a multiple hop

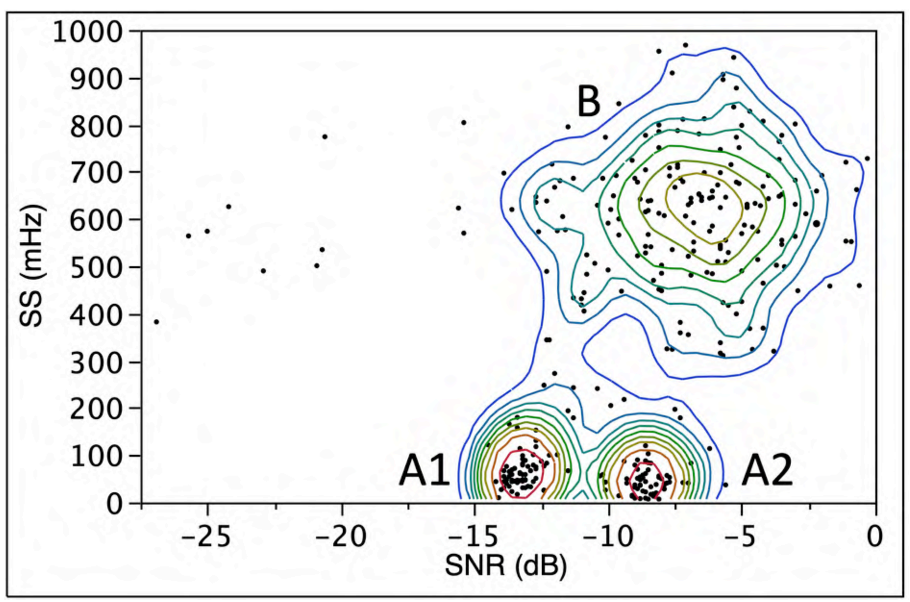
Using PyLap to plot possible rays, we suggest that side scatter occurs where there is maximum density of ray landing (both ways)

- TX from G3ZIL
- TX to OE9GHV



2 Hop Side scatter on a 40 km path on 14 MHz

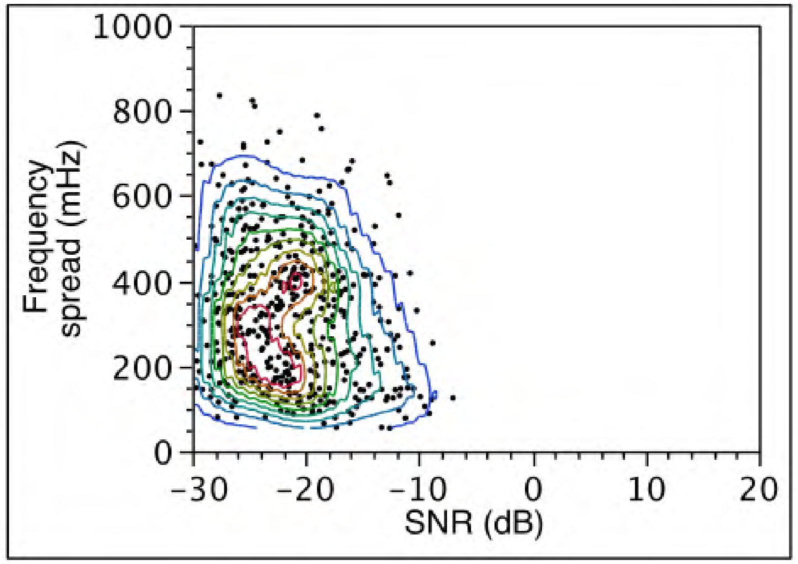




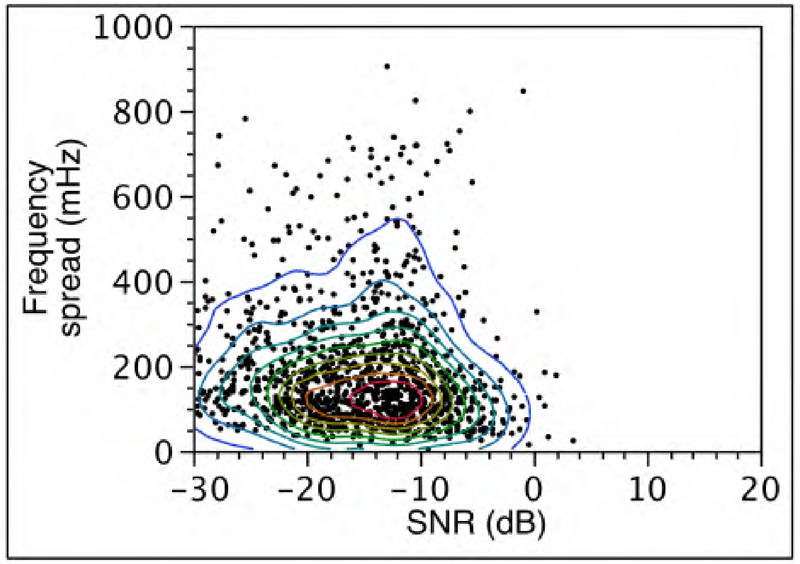
A1 and A2 are ground wave

B is characteristic of 2 Hop side scatter

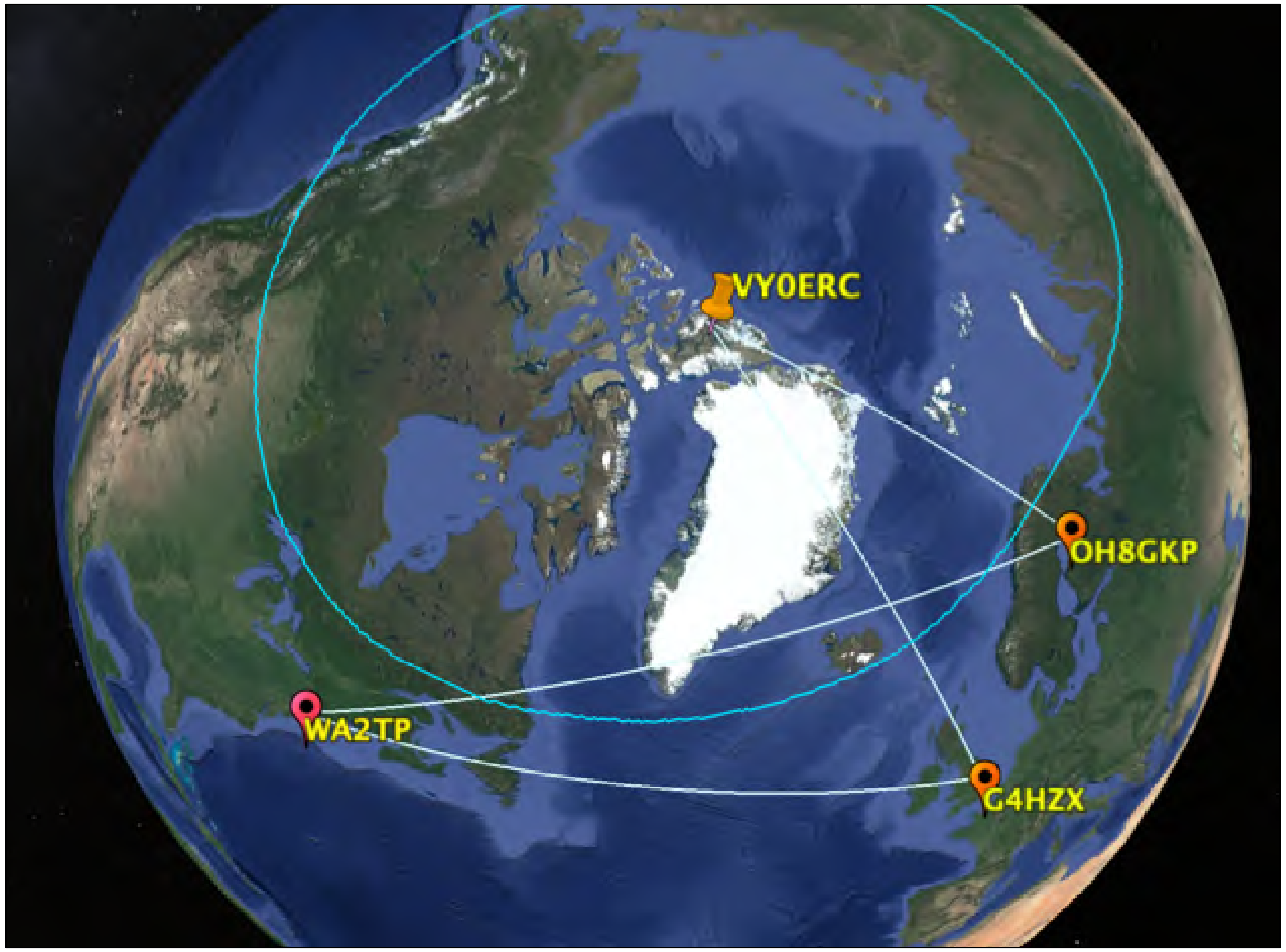
Comparison of Trans-Auroral Oval and Trans-Atlantic paths on 14 MHz



OH8GKP to WA2TP 6340 km 479 spots

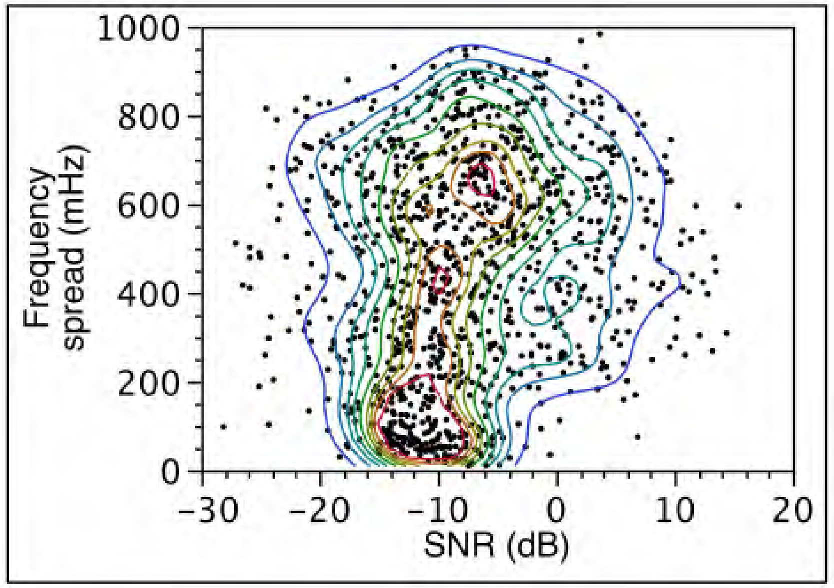


G4HZX to WA2TP 5505 km 1178 spots

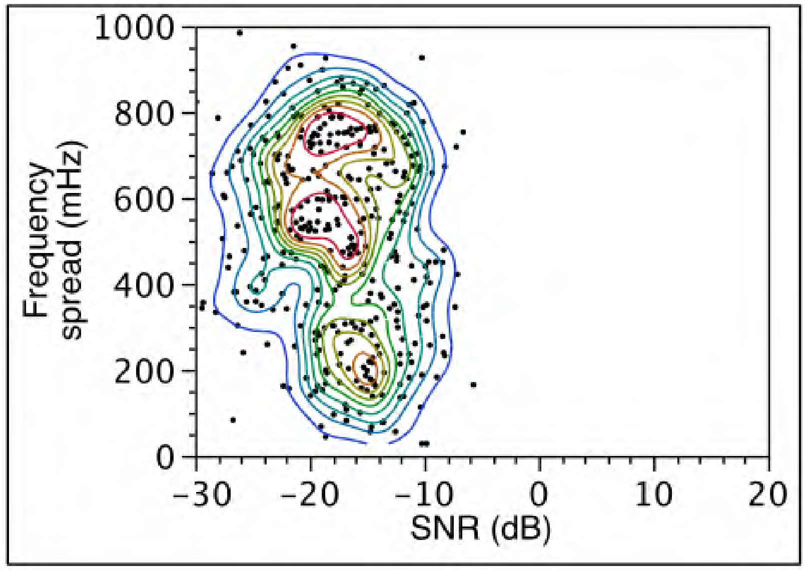


Transatlantic path is more reliable - lower spread and more spots than path along the Auroral Oval

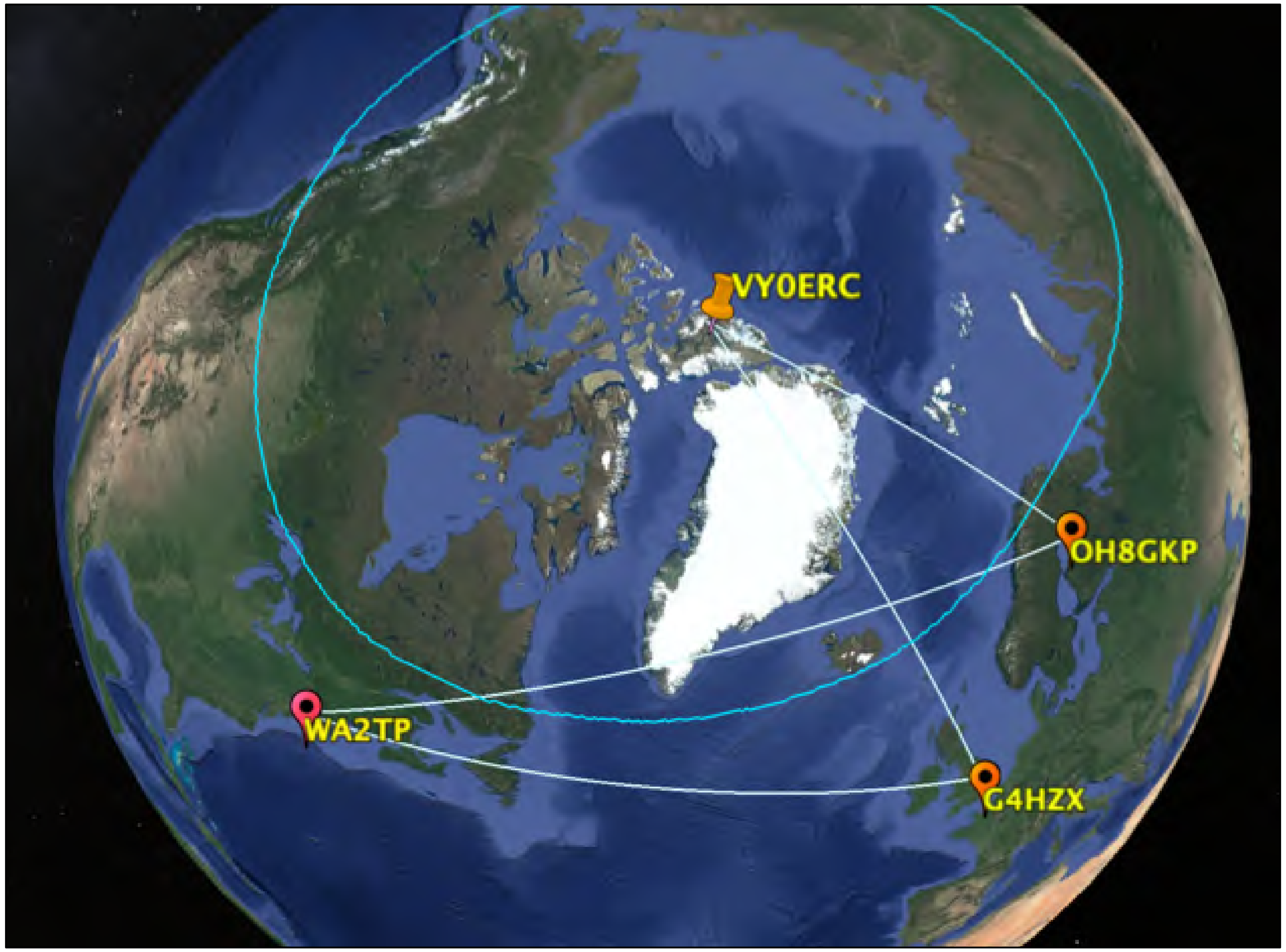
Comparison of Trans-Auroral Oval and Trans-Atlantic paths on 14 MHz



OH8GKP to VY0ERC 3360 km 1078 spots



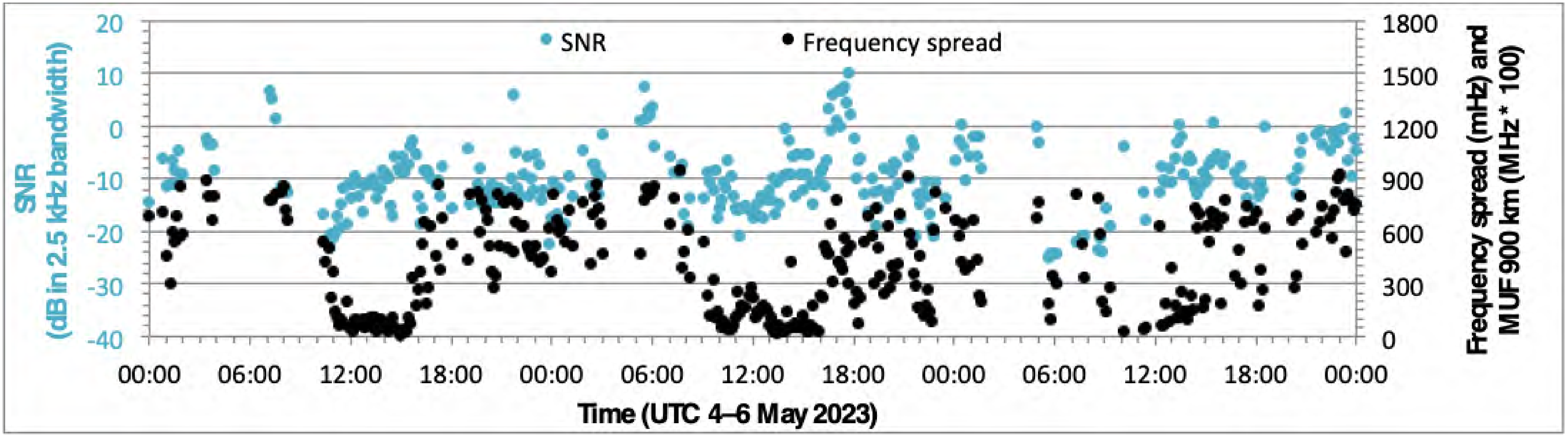
G4HZX to VY0ERC 4337 km 374 spots



Within the Trans-Auroral Oval path is more reliable - lower mean spread and more spots than path starting outside the Oval

Further work : Causes of low- and high-spread modes not yet clear

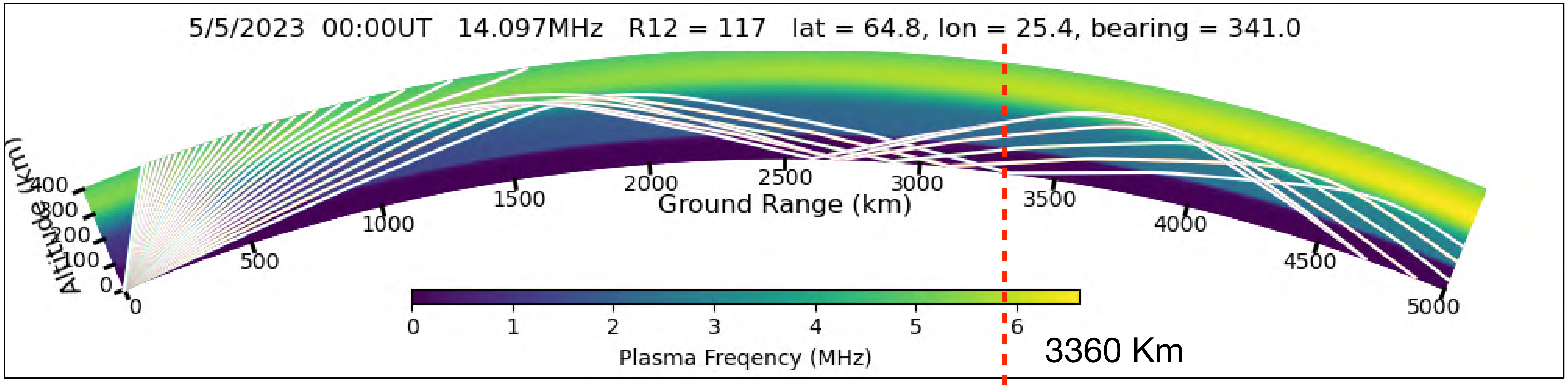
Example - OH8GKP to VY0ERC. 14Mhz, 3360 Km



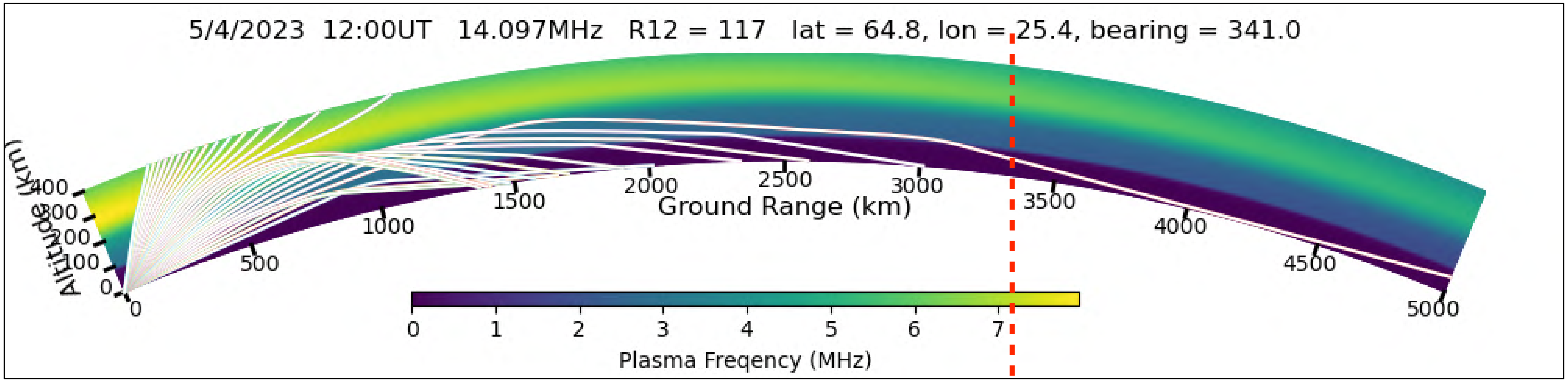
What is going on here ?

- Zero spread at 12:00 UTC suggests Pedersen Ray, but SNR is quite high
- Pylap (see next slide) suggests that spots at 00:00 are single hop, but spread is too large

Further work : Causes of low- and high-spread modes not yet clear



Pylap suggests single hop at 00:00 UTC, spread data does not confirm this



Pylap suggests Pederson Ray at 12:00 UTC, SNR does not confirm this

There is much more work to be done