Identifying 14 MHz propagation modes using FST4W SNR and spectral spread

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Slide 1

Good day. My aim is to show you why FST4W - a relatively new beacon mode within the WSJT-X package - is a really useful propagation analysis tool at HF even though it was designed specifically for use on LF and MF bands.

My colleague Rob Robinett will speak next on the "how".

I'm grateful to many people for making this work possible, credits to others will appear later.

Slide 2

In my presentation at last year's HamSci on the sudden collapse of WSPR decodes across North America on 7 MHz during the 4 November 2021 geomagnetic storm I could not determine whether the likely cause was reduced SNR, excessive Doppler spread or both.

When seeking a way to find an answer I discovered that the FST4W mode in WSJT-X can be made to measure spectral spread.

This presentation is all about how I've learnt to use spectral spread alongside SNR to associate their combined 'fingerprints' to different propagation modes. I can also now show when geomagnetic disturbance leads to sufficient Doppler spread to cause spots not to be decoded.

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FST4W is a WSPR-like beacon mode optimised for use on the LF and MF bands but with several differences. One difference is that it has four sequence lengths. This talk is almost exclusively on the 120 second variant that works on global paths at HF.

Its two performance advantages over WSPR are not central to this study. Rob will show how to overcome its disadvantages, but I thank John Seamons at KiwiSDR and Hans Summers at QRP Labs for the significant reductions in phase noise that they made to enable the measurements I'll show today.

Setting the option to measure spectral spread is unconventional and awkward - an empty file named plotspec must be put in the directory in which WSJT-X is run.

We can now say whether a spot decode failed because of excess spectral spread or because of insufficient SNR. In this example of a failed decode, the spectrum of an FST4W-300 spots is in blue, the noise in red. Failure was **not** because of lack of SNR it was because of excess spectral spread.

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I'll show results from two experiments. First, December 2022 with transmissions from Lynn Rhymes WB7ABP Santa Rosa California to receivers at the sites shown with yellow map pins.

The second, complementary experiment, in February 2023 used transmissions from my QRP Labs QDX digital transceiver with an external GPSDO clock at Southampton, UK to VY0ERC at Eureka, Ellesmere Island across the Auroral Oval, and to K6RFT Missouri to examine Ionosphere-to-Ionosphere modes.

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The December 2022 experiments gave a variety of paths from a 2.4 km partially obstructed ground wave path, through what turned out to be a fascinating set of paths spanning 40 to 1000 km, and out to over 3000 km to the east, north and west.

For data analysis I mainly used time series graphs and scatter plots of FST4W spectral spread against signal level or SNR with non-parametric density contours that greatly aided interpretation.

Ray tracing using PyLap was invaluable for checking what propagation modes might be supported over particular paths at particular times.

I confess to a great deal of head-scratching when trying to interpret several of the graphs, but the answers were in the literature, while discussion with amateur friends provided sanity checks. Nevertheless, I'd welcome comments and insights from professionals.

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Let's look at the 40 km path from Santa Rosa to the coastal radio station KPH at Point Reyes. A reminder, this is at 14 MHz, and transmit and receive antennas are horizontally polarised.

As the terrain profile shows, this is not line of sight.

In the time series graph at left the signal level of FST4W spots at the receiver input are in blue, read on the left hand scale, and the spectral spread in milliHertz are in orange, read on the right hand scale. The cyan humps represent the sun elevation angle at the mid point of the path so we can judge local time of day.

In the scatterplot at right the spectral spread is on the y-axis and the signal level on the x-axis. The density contours help interpretation when we are dealing with several hundred spots. The contours bring out the clusters, which have been a nice surprise to me.

I'm proposing that the period marked A on the time series graph, at night, characterised by low signal level and low spectral spread, and present as two clusters in the scatterplot, was ground wave propagation. There's clearly day-to-day variation of the ground wave level in the time series and scatter plots.

But what propagation mode is responsible for cluster B? Whatever mode it is, it produces higher signal level than ground wave and has about ten times the spectral spread. It is very unlikely to be near vertical incidence sky-wave at 14 MHz and 40 km.

Have a think and we'll return to this question shortly.

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I had hoped that the picture at a range of 960 km would be easier to interpret - but it's not. Here the path is from Santa Rosa to the Northern Utah SDR site reporting as KA7OEI dash one.

I've labelled three clusters on the scatterplot and then picked them out on the time series graph. I'll only consider I1 and I3 today.

I1 was a daytime mode, with the highest signal level and SNR, and a median spectral spread of 87 mHz.

I3 immediately followed I1 in time, which is a useful piece of information, but with a signal level some 20 dB lower. Its median spectral spread was 622 mHz - a value very similar to mystery mode B on the 40 km path to KPH.

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Let's turn to a propagation model and ray tracing to help identify cluster I1, or at least to confirm what we may strongly suspect to be the mode.

The single daytime SNR peak in the propagation model and the PyLap rays for 2000 UTC - daytime in Utah - show that **I1 was one-hop propagation via the F2 layer.**

By 0200 UTC the maximum usable frequency had dropped and the receiver at a range of 960 km was well within the skip zone.

By 0500 UTC rays at all angles travelled through the ionosphere, at least in this model.

We're left with the question, "What was the mode for cluster I3?"

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Let's look at a candidate "Above the MUF" mode - I've skipped much reading and head scratching to get here - the mode we'll look at is two-hop side scatter. It is mentioned in the ARRL Handbook and is well described in several readable papers and reports with numerous examples and descriptions of neat techniques for identifying signals received via this mode.

Looking at the map the clear area centred on Santa Rosa is the skip zone at 0200 UTC, 1800 local time, at 14 MHz. The Northern Utah SDR site is within this zone.

But ... one hop propagation **is** possible into the shaded region. My cartoon shows one possible scenario - this is one out of many - I have no evidence for choosing this scenario over others. The rays in brown propagating from Santa Rosa will undergo ground scatter - with the forward-scattered energy going on its way to the south. But the interaction is scatter, it is not specular reflection as for a mirror, and there will be energy scattered at all angles. From each area on the ground (or in this example, the sea) there will be side scatter along paths that lead to the receiver.

On each of the outward and return paths there's one-hop propagation via the F layer, and hence the term two-hop side scatter for this mode.

The ITU P.533 model has a simple expression for the excess loss for two-hop side scatter. We can use this estimate to test whether this mechanism produced the cluster I3.

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I estimated the basic MUF at the times of the I3 clusters from data from the closest Digisonde, at the Idaho National Lab one hundred and ninety five km north of the KA7OEI dash one receiver.

The seven dB difference between excess loss from the simple model in ITU P.533 and the measurement was fair for KA7OEI dash one. And it has to be just good fortune that there was zero difference for the 679 km path from Santa Rosa to KK6PR in Oregon. As you can see, the I3 cluster of spots dominated at KK6PR.

On the basis of this reasonable match between modelled and measured excess loss, and that I3 immediately followed in time the one-hop F2 layer propagation at KA7OEI-1, as the MUF dropped below 14 MHz, I conclude that I3 is two-hop side scatter.

Furthermore, mystery daytime clusters B at KPH at 40 km, and at KP4MD at 133 km from the transmitter were also two-hop side scatter.

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Now we look at the three thousand seven hundred and two km path from Santa Rosa to Maui. We have two modes to identify.

PyLap ray tracing shows that I5 was most likely two-hop F2 layer propagation during daytime. The median spectral spreading was 266 mHz, very similar to the two-hop path to Long Island, New York at 277 mHz. But it would be interesting in a further study to compare spectral spread on two-hop paths over land and sea in detail.

What is clear is that spectral spread on two-hop paths is over twice that of one-hop paths, as to why, that's another topic to study with FST4W.

What of I6? It has a lower SNR, some 45 dB below that of two-hop propagation. But it is not a side scatter mode, as its median spectral spread of about 83 mHz is typical of singe hop.

PyLap suggests single-hop refraction may have been possible - but it was fleeting - in the model it existed for tens of minutes, not four hours as here. Might I6 be ionospheric scattering? Or some other mode?

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Changing our operating area to the Trans-Atlantic I'll look at three paths from here in Southampton, UK. First we'll look at a comparative pair, a mid latitude path to WA2TP Long Island and a Trans-Auroral Oval path to VY0ERC at Eureka on Ellesmere Island.

The map shows the paths, with an overlay of the far UV auroral glow from a US defence satellite to indicate the typical position of the Auroral Oval over central Greenland.

The left scatterplot clearly shows higher spectral spread on the trans Auroral Oval path, the purple squares, versus the mid latitude path, the green dots.

Looking at the scatter plot of spectral spread on the y axis with Kp, a geomagnetic disturbance index on the x axis shows that decodes were far more numerous when Kp was at or below two than when at three, unsettled, or above. As Kp increased there were fewer instances of modest, below 400 mHz, spread. It is likely that many signals at Kp over two had spreads of over 900 mHz, off the top of this graph, and not decoded.

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The third Trans-Atlantic path and my final example is over the almost 7000 km path from Southampton UK to Houston Missouri and K6RFT.

The scatterplot top right of spectral spread against time of day with spreads mostly between 400 and 600 mHz each side of 1200 UTC suggests three or four hop F2 layer propagation.

More intriguing are the clusters around 0800 UTC when almost the entire path was in darkness. Especially interesting is a tight cluster of nine spots with less than 100 mHz spread on the 18th of February, as a spread of less than 100 mHz is what I've come to associate with one-hop propagation.

The spectral spread against SNR scatterplot, top left, shows that some of the decodes with less than 100 mHz spread had far higher SNR than those around midday via three or four hops.

PyLap suggests that an ionosphere-to-ionosphere choral hop mode could have been present around 0800 UTC. Perhaps those decodes with low spread and SNR below, perhaps, minus 15 dB were indeed via chordal hop.

And, speculatively, but perhaps not unreasonably, those with low spread and the highest SNR, propagated in a duct between the F layer and the top of the E layer, with less absorption than if the signal partly travelled through the lower ionosphere as in a chordal hop.

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To summarize, FST4W is certainly not just of use on the LF and MF bands. Its one hundred and twenty second variant is capable of global paths with the right equipment. FST4W's option to estimate spectral spread should be a tick-box, in capitals, bold, and underlined. I do think it really is that useful. It brings a new measurement capability to low cost amateur radio citizen science. Spectral spread estimates make FST4W a propagation analyzer and not merely a reporter.

I've shown how simple scatter plots and time series of spectral spreading can identify several HF propagation modes, from simple one and two hop F2 layer refraction to two-hop side-scatter and ionosphere to ionosphere modes.

It'll be fascinating to use FST4W to study the response of the fast depletion-replenishment of the region below the F layer peak during the 2023 and 2024 solar eclipses. As for what equipment you'll need, that's the subject of Rob's upcoming talk.

Thank you.