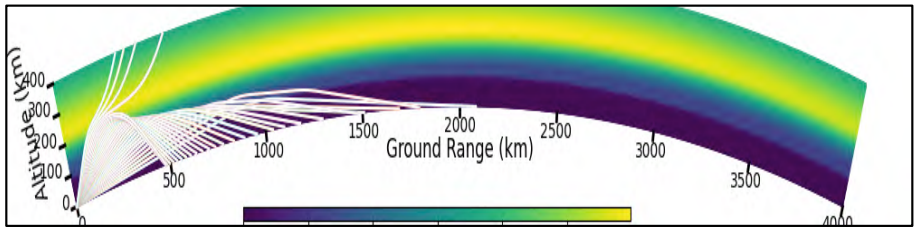
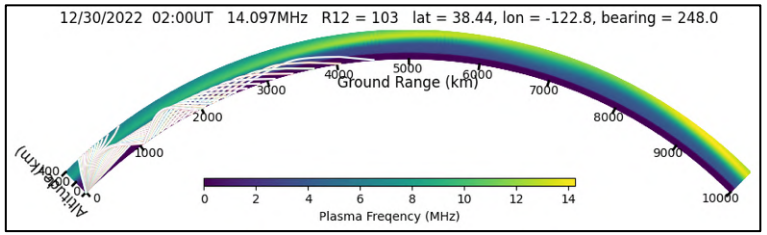
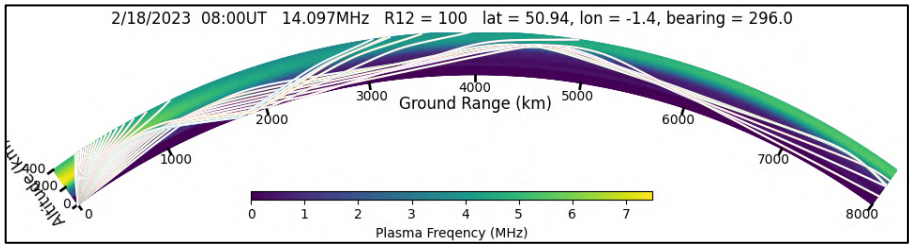
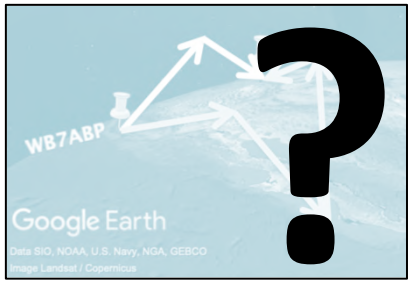
Propagation at HF: What can we learn using digital modes WSPR and FST4W?

Gwyn Griffiths G3ZIL



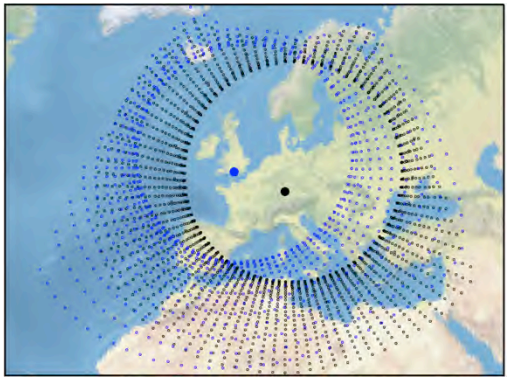




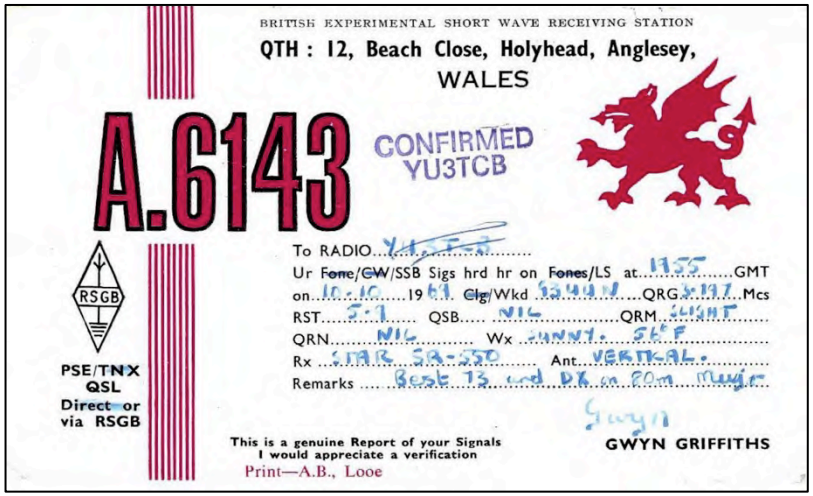


Outline

- About me
- My return to amateur radio 2015, discovery of WSPR.
- Why do WSPR spots disappear?
- How *did* signals get from here to there?
- The usefulness of digital modes for propagation analysis.



1969/70: A.6143 to GW3ZIL


BRITISH EXPERIMENTAL SHORT WAVE RECEIVING STATION

QTH : 12, Beach Close, Holyhead, Anglesey, WALES

A.6143

CONFIRMED YU3TCB

PSE/TNX QSL Direct or via RSGB

To RADIO...

Ur Fone/CW/SSB Sigs hrd hr on Fones/LS at...1155...GMT

on...10-10...19 61 Clg/Wkd 1344 N...QRG 14197...Mcs

RST...5-1... QSB... NIL ...QRM...SLIGHT

QRN...NIL... Wx ...SUNNY. 56°F

Rx ...STAR SR-550... Ant...VERTICAL.

Remarks ...Best 73 and DX on 20m Mwjr

Gwyn

This is a genuine Report of your Signals I would appreciate a verification

GWYN GRIFFITHS

Print—A.B., Looe

Lucky to have had true mentors:
Cyril GW3OIM, operating
Paul GW3MQX, CW, aerials and rigging
Alan GW3NNF, engineering

Today's shack

SWL A.6143: PCR receiver

GW3ZIL:
Star SR550 receiver
KW Viceroy transmitter

Oceanography: Engineering and applied science

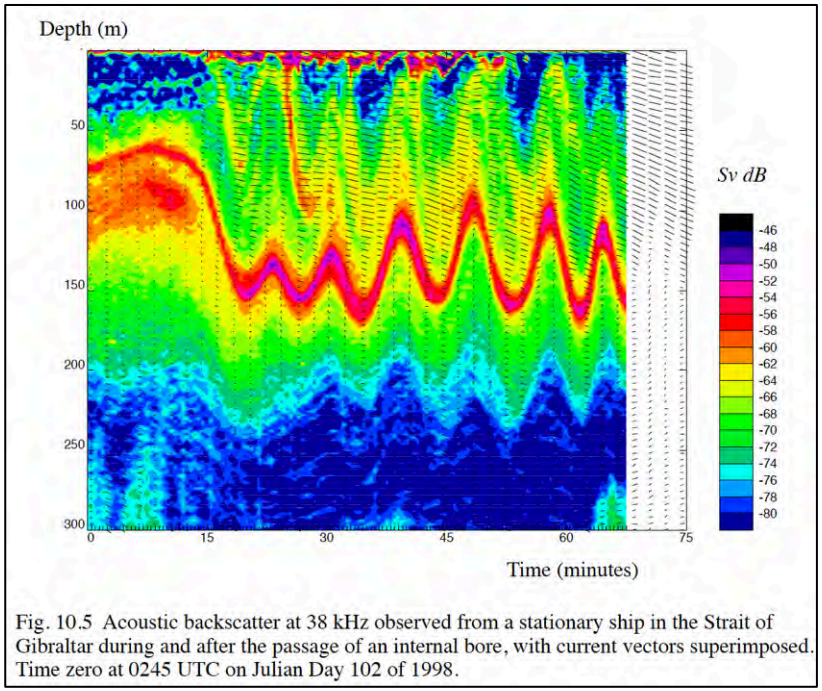


Fig. 10.5 Acoustic backscatter at 38 kHz observed from a stationary ship in the Strait of Gibraltar during and after the passage of an internal bore, with current vectors superimposed. Time zero at 0245 UTC on Julian Day 102 of 1998.

Internal waves in the Strait of Gibraltar from shipboard sonar backscatter. Atlantic water above, Mediterranean water below.

Design and operation of sonar systems to observe the ocean.

Interpretation of the resulting data.

Subsequently, autonomous underwater vehicles (‘*Boaty*’).

WSPR receiver: Improvements and setbacks

Feature by Gwyn Griffiths G3ZIL

Gwyn Griffiths G3ZIL • E-Mail: gxgriffiths@virginmedia.com

A Direct Conversion WSPR Receiver for 30, 40 or 60 metres

Gwyn Griffiths G3ZIL describes a WSPR receiver that is a great project to build and even more to use as part of the worldwide WSPR reporting system.

The author's latest version, in development. This uses the main board as described in the article plus an Arduino clone with a QRP Labs Arduino shield and a QRP Labs Si5351A synth for the local oscillator. It covers up to five bands with a QRP Labs relay switched board with the author's own size-compatible plug-in single-crystal filters.

WSPR segments, the ideas and most of the circuitry I'll describe could, with some experimentation, be adapted for use on other bands.

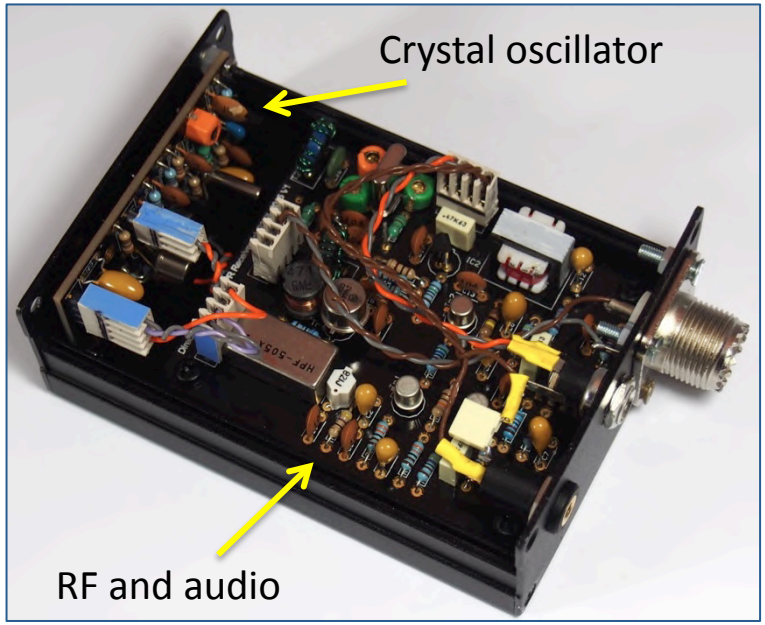
http://tinyurl.com/h5sd3a9
http://physics.princeton.edu/pulsar/K1JT/wspr.html
http://wsprnet.org/drupal

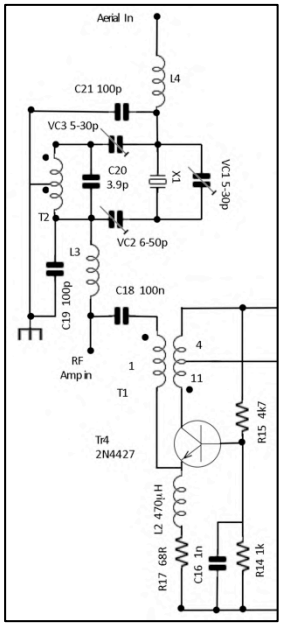
The Circuit

I make no claim of originality for the elements of the receiver's circuit, **Fig. 1**. It owes a great deal to **Gene Marcus W3PM/GM4YRE** who published online a design for a 1W WSPR transceiver for the 30m band, URL below. In turn, he drew on ideas from **Rick Campbell KK7B** for the crystal filter and AF preamplifier.
www.knology.net/~gmarcus/WSPR/wspr_v4.pdf

The input is for a 50Ω antenna, through an L-section matching network to a single-crystal filter. Suitable crystals at 10.140MHz, 7.040MHz and 5.290MHz are readily available for the 30, 40 and 60m WSPR segments. There is no reason why other bands could not be covered if crystals were available, for both the filter and the local oscillator.

The filter's main purpose is to provide a



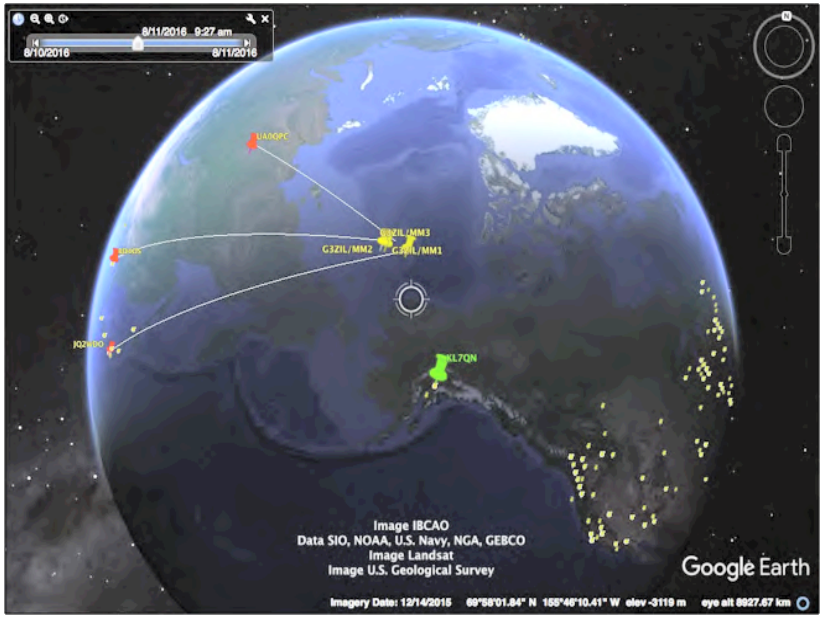


'2016 model'. W3PM design plus David Norton's "noiseless feedback' RF pre-amp and modified crystal oscillator on two PCBs.

Practical Wireless April 2016

WSPR on an Icebreaker

- 10 MHz version onto a Korean research icebreaker RV *Araon*, August 2016 north of Alaska.

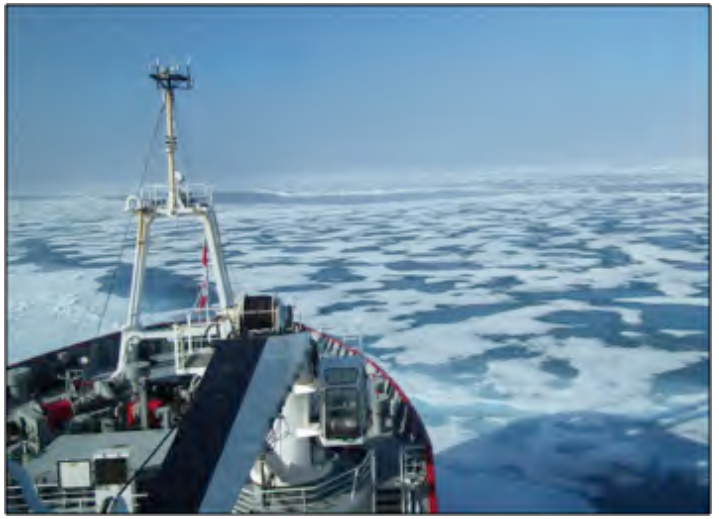


Date & Time	Call	Freq (MHz)	SNR (dB)	Grid	Watts	MyGrid	dist (km)	delT (s)
2016-08-11 09:06	JQ2WDO	10.140190	-24	PM95gi	5	AQ45	5152	-0.3
2016-08-11 09:48	BD4OS	10.140166	-24	PM17bm	2	AQ35	5294	6.0
2016-08-20 13:00	UA0QPC	10.140138	-6	OP66dj	10	AQ95	2976	-3.0

Credit: Korea Polar Research Institute and Dr Jeremy Wilkinson, British Antarctic Survey

WSPR on Royal Research Ship *James Clark Ross*

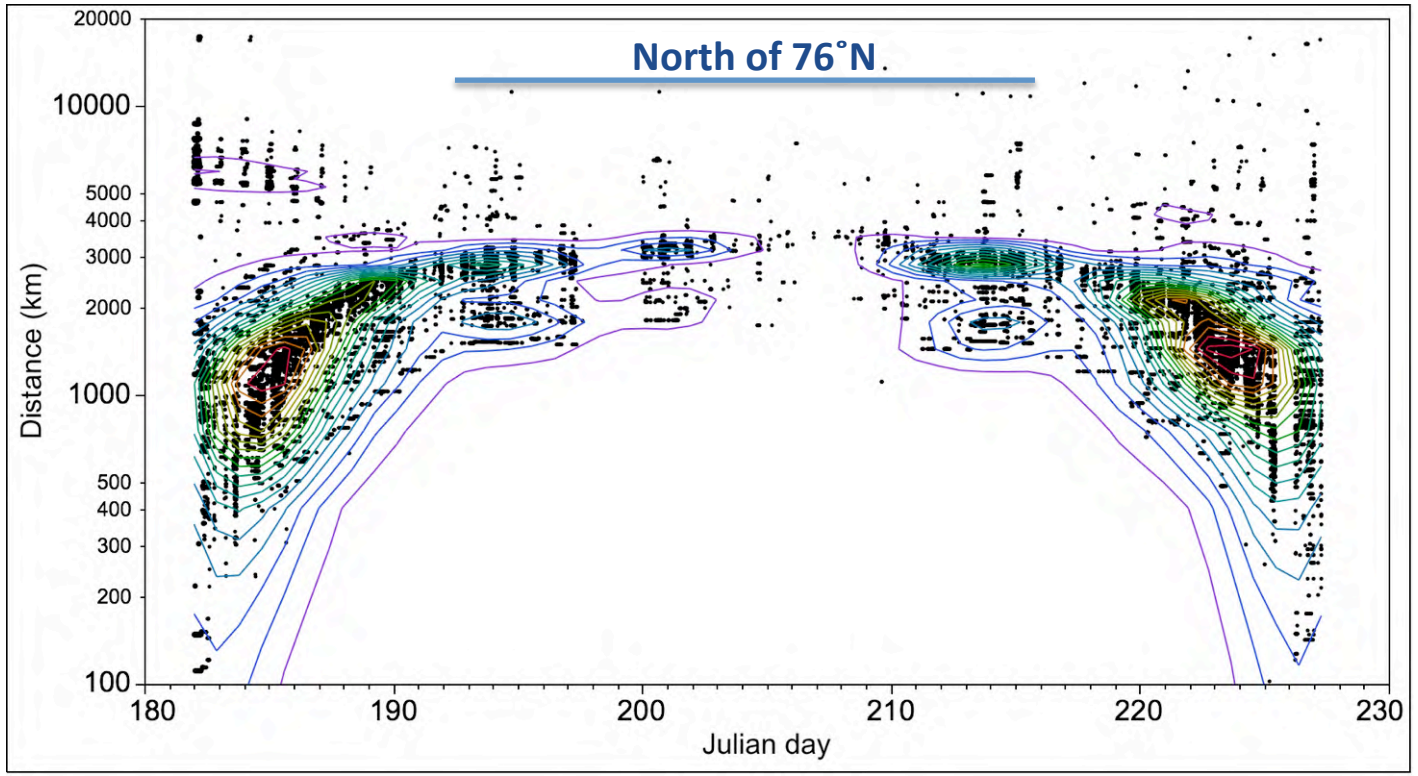
- Collaboration with **Mike Gloistein GM0HCQ**, Radio Officer on the *JCR*.
- July-August 2017 voyage UK to Svalbard and back.
- 10 MHz WSPR reception with ship's Sailor HF receiver and a 10 m vertical antenna.
- Spots reported via satellite except 17 Jul – 4 Aug when too far north, uploaded later.
- Article in Sept. 2018 RadCom.

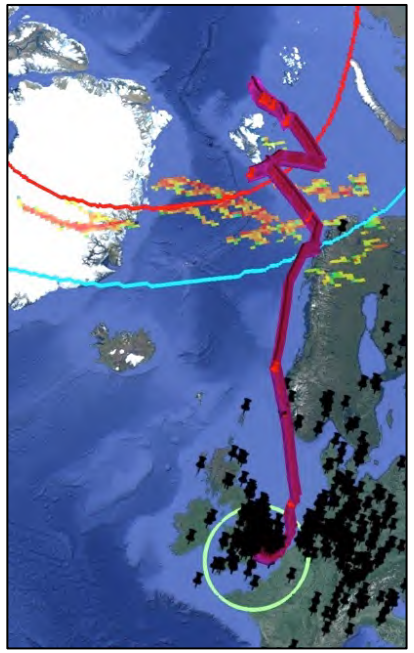


Credit: Mike Gloistein GM0HCQ

WSPR on Royal Research Ship *James Clark Ross*

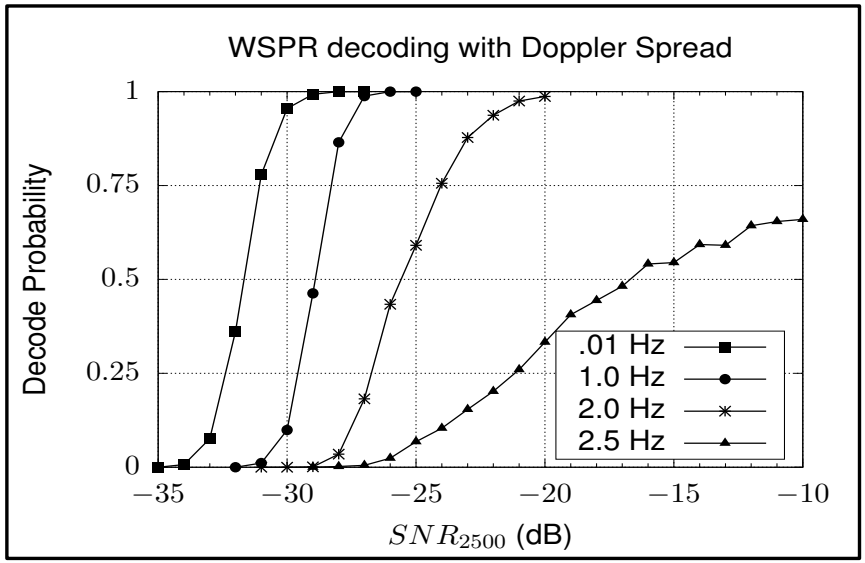
Southampton Tromso Tromso Southampton





Credit Google Earth Landsat/Copernicus, IBCAO, USGS.
Auroral data ssusi.jhuapl.edu/gal_edr-aur_cs

WSPR spot decode probability: SNR and Doppler spread



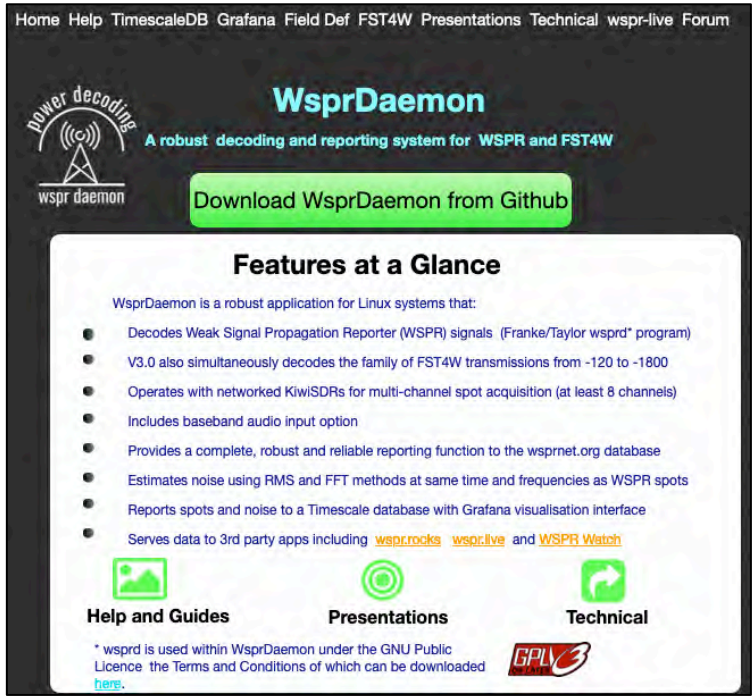
Graph and modelling courtesy Steve Franke, K9AN.
Based on, "*Testing of HF Modems … Using Iono-spheric Channel Simulators*", ITU-R F.1487, ITU, 2000.

- Stress that SNR is reported in 2500 Hz bandwidth, much wider than 6 Hz transmission and reception bandwidth.
- Assumes transmit callsign seen before, no delay and Gaussian frequency spreading.
- Outcomes:
  - 'Graceful degradation' of decode probability to spread of 2 Hz.
  - 50% probability decode at -17 dB SNR at 2.5 Hz spread.

Here spread measured between -10 dB points of the spectrum.
Others use width between -3 dB points, so about 40% of these values.

How can I measure frequency spread of WSPR spots?

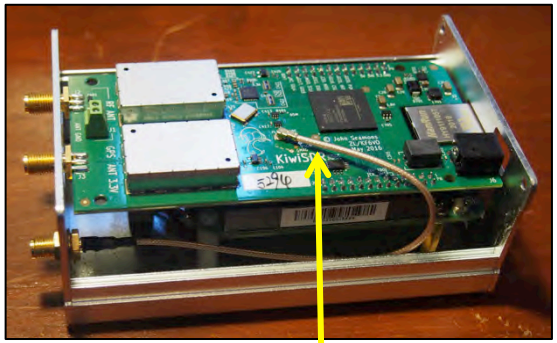
- I couldn't. But…
  - WSJT-X 2.3.0 added FST4 and FST4W, "*digital protocols designed particularly for LF & MF*".
  - FST4W measures frequency spread if an empty file *plotspec* in start-up directory.
- However:
  1. How do we log the new frequency spread variable?
  2. *No documented use or users at HF.*
  3. *We won't want equipment frequency spread (oscillator jitter, or phase noise) contaminating results.*
  4. *There's no drift compensation in FST4W.*



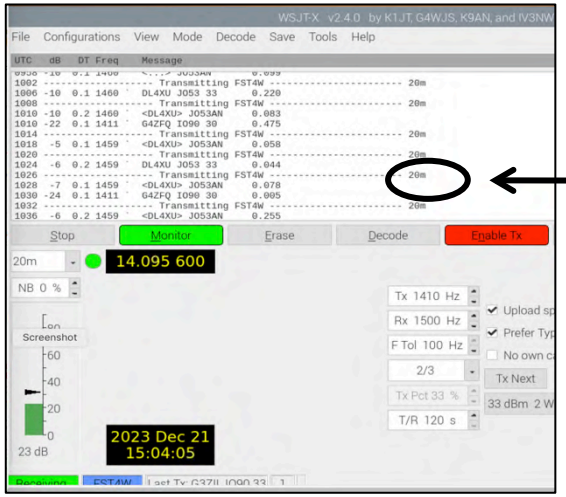
wsprdaemon.org
Rob Robinett AI6VN

Receive sites: Majority used KiwiSDRs

Coffee Catz



Ext GPSDO clock

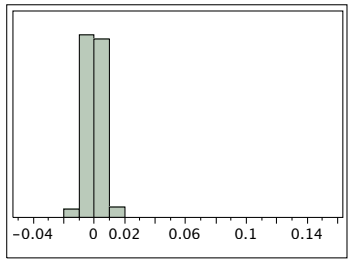


Doug WW6D used an ELAD FM Duo, 10 MHz external OCXO, with standard WSJT-X. He needed to copy the screen for frequency spread values.

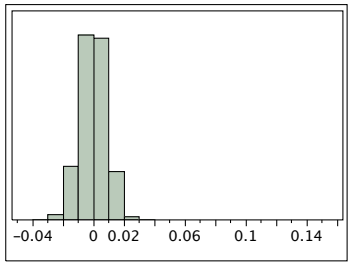
- Cluster of interested amateurs in Northern California ('Catz') and wider USA already using WsprDaemon.
- *As standard, KiwiSDR is GPS-aided*, not phase locked GPSDO.
- External phase-locked GPSDO can be connected.

Transmit site: WB7ABP, Santa Rosa

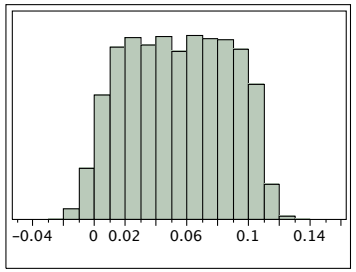
- Apache ANAN-100D SDR transceiver
  - FST4W-120, the two-minute variant
  - 5 W output
  - GPS Disciplined Master Oscillator
- Thanks to **Lynn WB7ABP**



Intrinsic frequency spread given duration of transmission.
Spread of 0.005 Hz



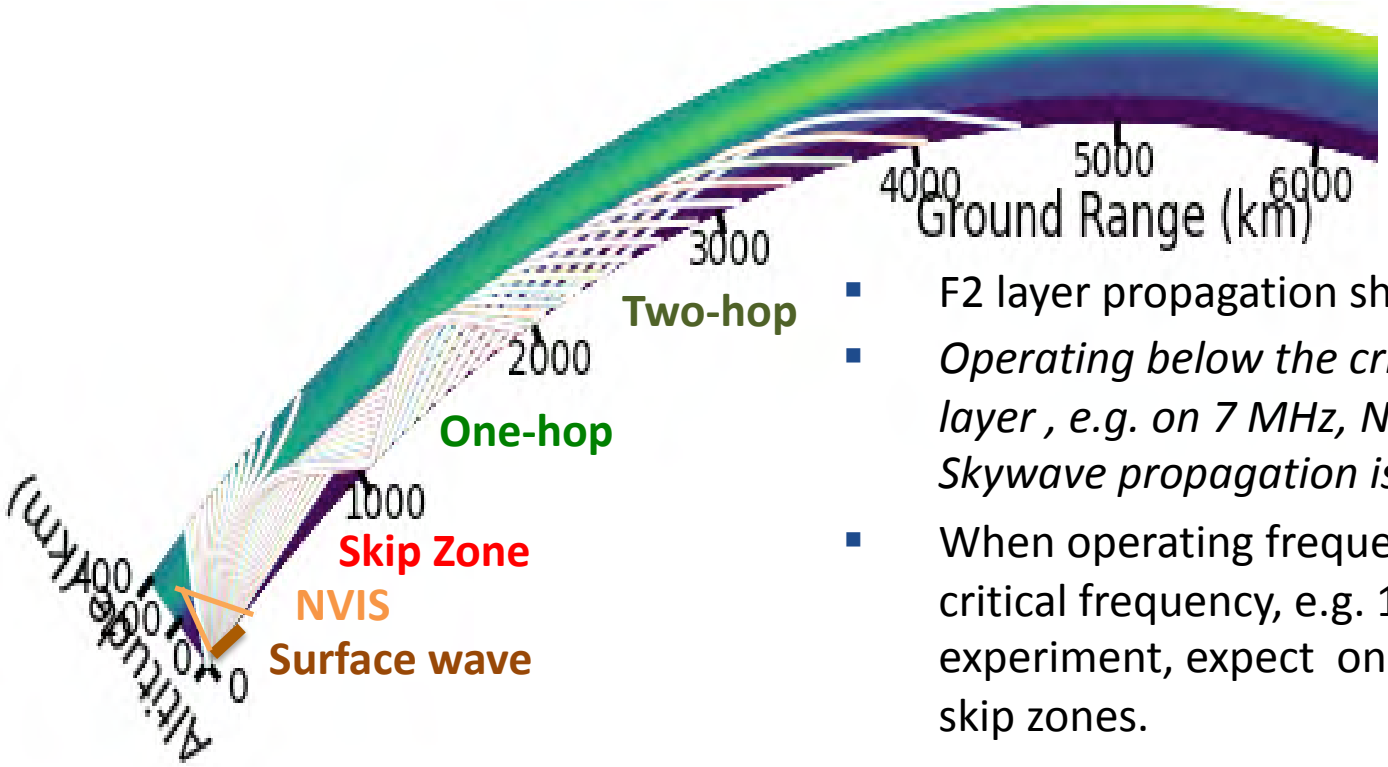
Intrinsic frequency spread and same spread, as jitter or phase noise, from Tx and Rx.
Spread now 0.008 Hz



If there was drift of 0.1 Hz over two minutes.
Spread now 0.11 Hz

X-axis frequency in Hz

HF propagation refresher



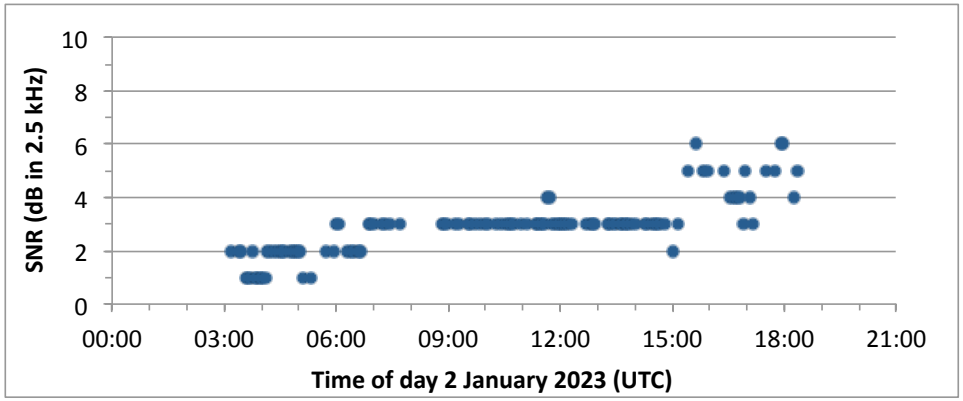
Ray tracing using PyLap

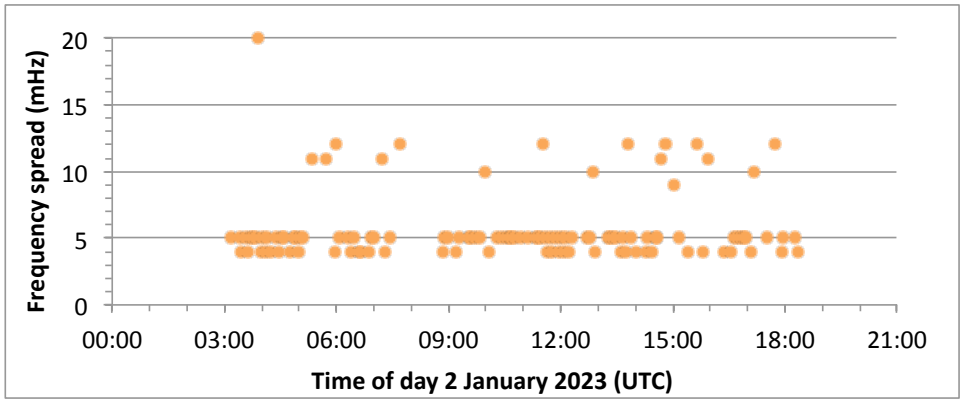
- F2 layer propagation shown as ray traces.
- *Operating below the critical frequency of the F2 layer , e.g. on 7 MHz, Near Vertical Incidence Skywave propagation is seen.*
- When operating frequency above the F2 layer critical frequency, e.g. 14 MHz as in this experiment, expect one-hop or multi-hop with skip zones.

December 2022 14 MHz trials

- Single transmitter, WB7ABP, Santa Rosa on 14 MHz.
- With ‘Catz’ group plus WsprDaemon friends Rick KK6PR, Dennis ND7M, Clint KA7OEI, Bryan KF6ZEO (INUVIK) and Tom WA2TP we gathered frequency spread data at 11 sites.
- Path distances spanned 2.4 km to over 4000 km. Over land, over water, and to the Arctic Circle.

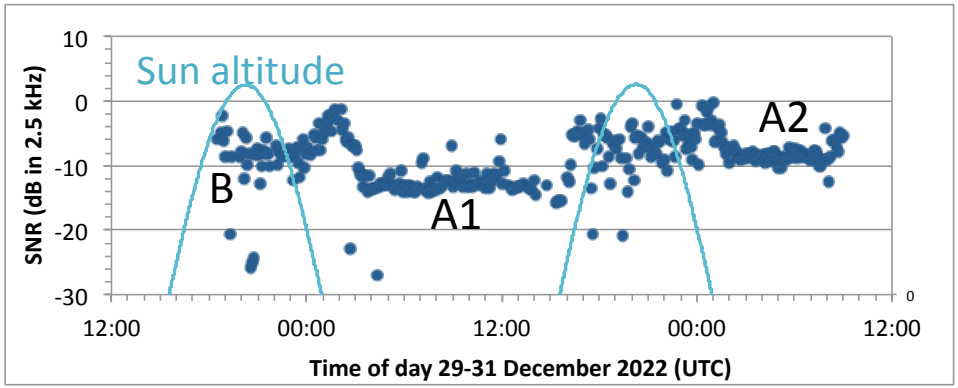
Line-of-sight surface wave 2.4 km: WB7ABP to WW6D

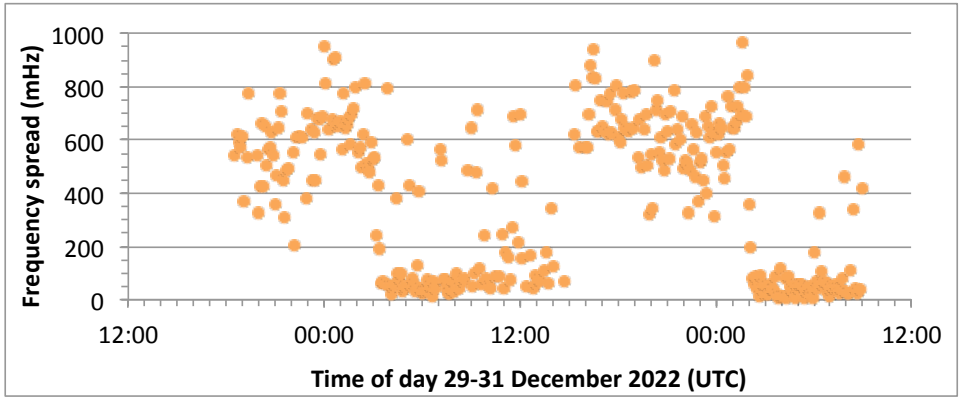


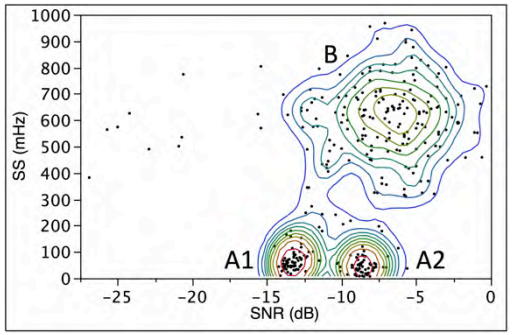


- Median frequency spread 5 milliHertz on this surface wave path.
- In fact 5 mHz is the minimum for FST4W even at baseband audio between two computers on a bench.
- Gives us confirmation of how low spread can be with GPSDO equipment.
- Should decode to -32 dB SNR threshold for surface wave signals.
- Thanks to **Doug WW6D.**

40 km path: WB7ABP to KPH





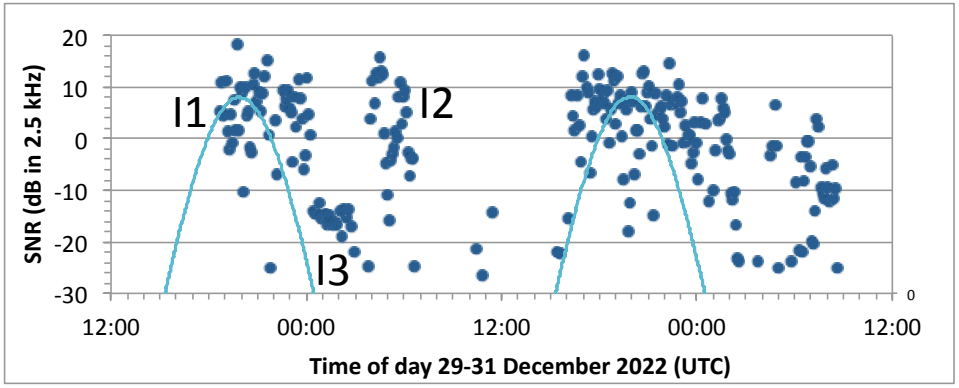


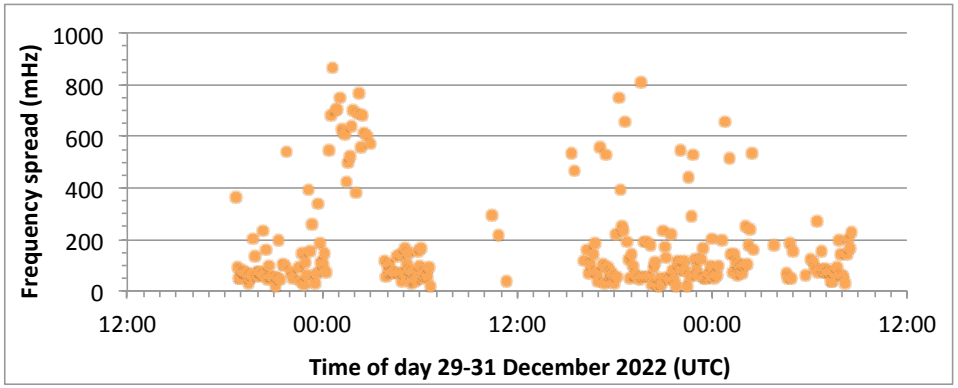
A1 and A2 surface wave on two nights.
Median spread 59 mHz.

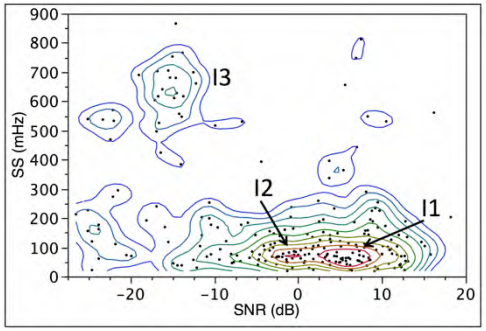
B is a daytime mode.
Median spread 624 mHz.

- KiwiSDR not phase-locked, GPS aided.
- Propagation not only surface wave.
- Two distinctively different modes.
- First mystery mode ‘B’.
- Thanks to **Maritime Radio Historical Society for KPH**.

960 km path: WB7ABP to KA7OEI







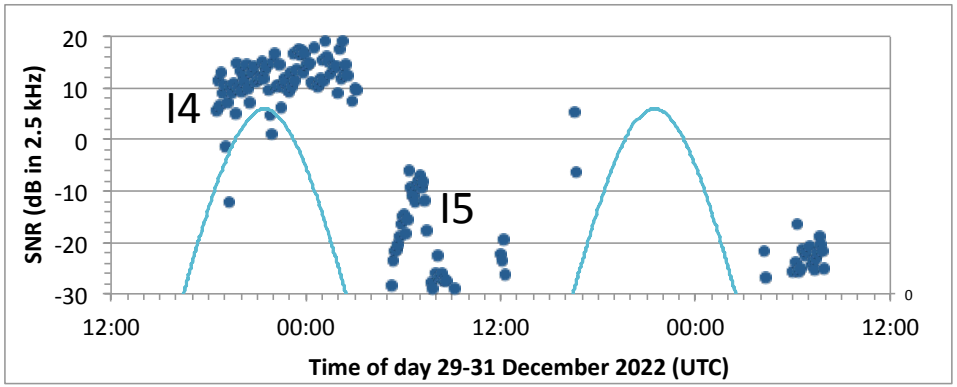
I1 one-hop F2 daytime.
Median spread 87 mHz.

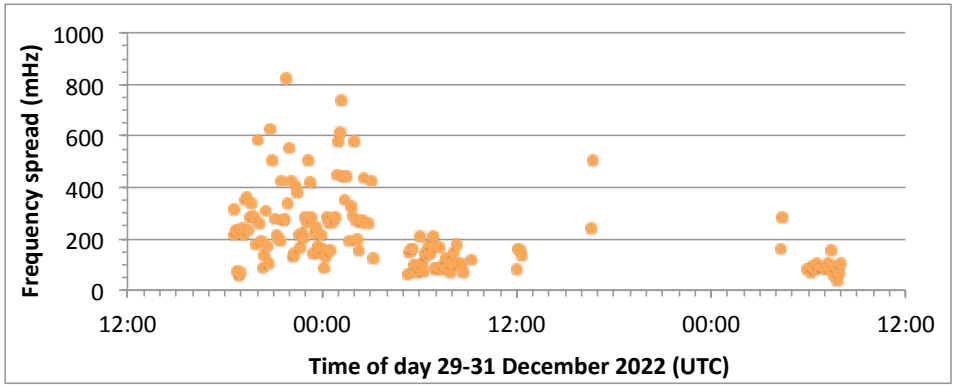
I2 night time mystery mode.
Median spread 77 mHz.

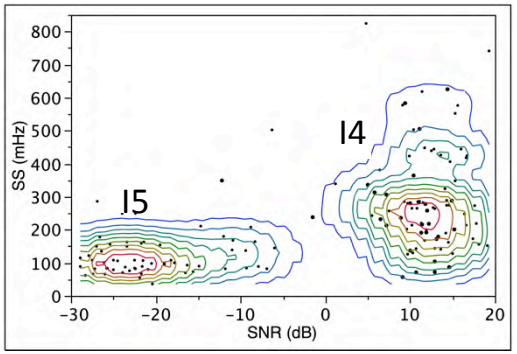
I3 evening mystery mode.
Median spread 623 mHz.

- KiwiSDR not phase-locked, GPS aided.
- One-hop: high SNR low spread.
- Two mystery modes. Might I3 be the same mode as B on the WB7ABP to KPH 40 km path?
- Thanks to **Clint KA7OEI.**

3762 km path: WB7ABP to AI6VN/KH6





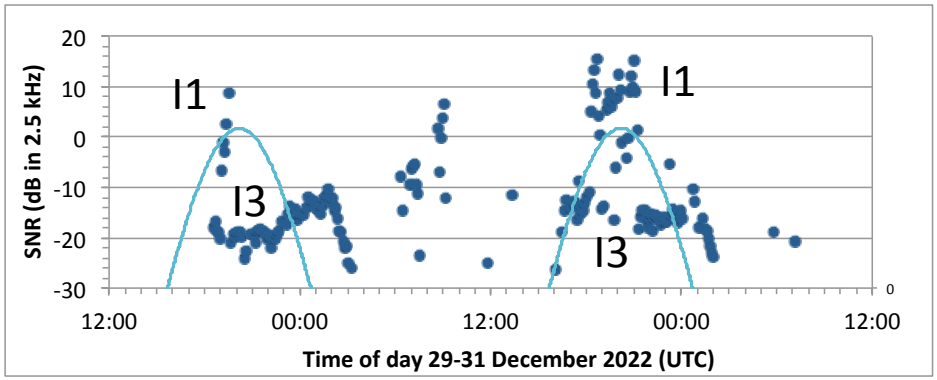


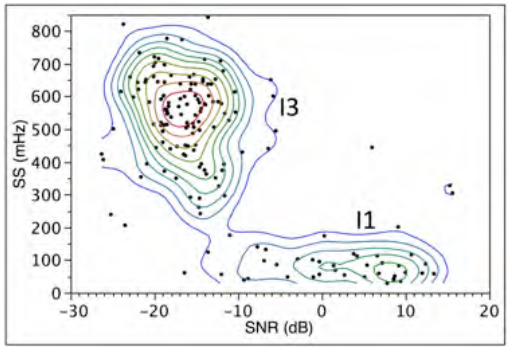
I4 two-hop F2 daytime.
Median spread 266 mHz.

I5 one hop F2 night time?
Median spread 83 mHz.

- KiwiSDR not phase-locked, GPS aided.
- Building a picture:
  - One hop spread <100 mHz
  - Two-hop spread about 260 mHz
- Mystery mode spread over twice two-hop.
- **Thanks to Rob AI6VN.**

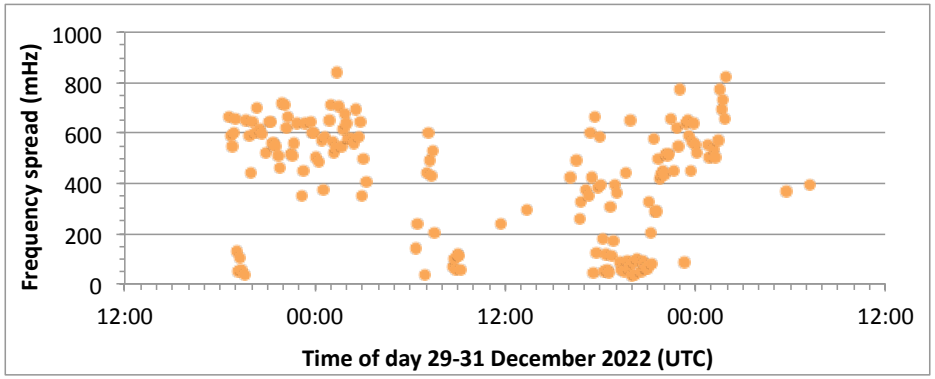
679 km path: WB7ABP to KK6PR





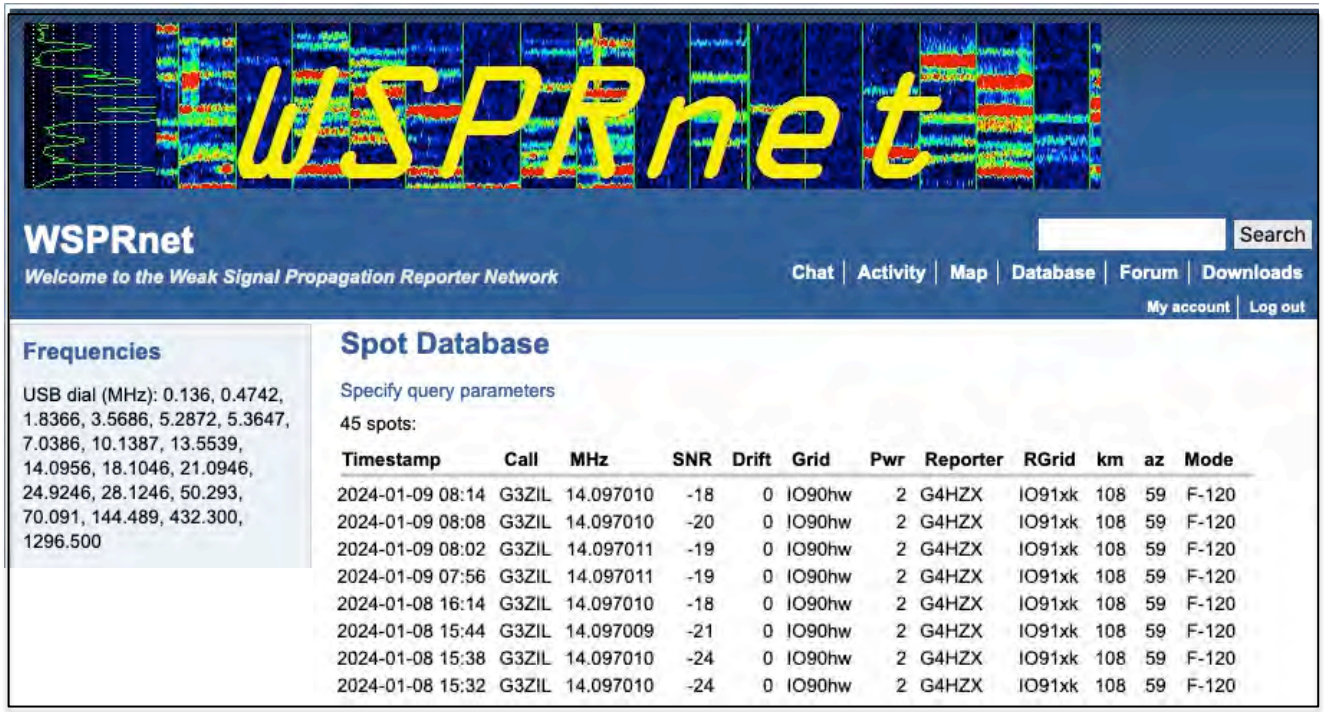
I1 one-hop F2 daytime.
Median spread 69 mHz.

I3 mystery mode.
Median spread 578 mHz.



- KiwiSDR not phase-locked, GPS aided.
- Mystery mode present ‘either side’ of one-hop F2 propagation.
- Likely one of several ‘*Above the basic Maximum Usable Frequency*’ modes: ITU report ITU-R P.2011
- Thanks to **Rick KK6PR**.

Why *does* G4HZX receive G3ZIL on 14 MHz?



Timestamp	Call	MHz	SNR	Drift	Grid	Pwr	Reporter	RGrid	km	az	Mode
2024-01-09 08:14	G3ZIL	14.097010	-18	0	IO90hw	2	G4HZX	IO91xk	108	59	F-120
2024-01-09 08:08	G3ZIL	14.097010	-20	0	IO90hw	2	G4HZX	IO91xk	108	59	F-120
2024-01-09 08:02	G3ZIL	14.097011	-19	0	IO90hw	2	G4HZX	IO91xk	108	59	F-120
2024-01-09 07:56	G3ZIL	14.097011	-19	0	IO90hw	2	G4HZX	IO91xk	108	59	F-120
2024-01-08 16:14	G3ZIL	14.097010	-18	0	IO90hw	2	G4HZX	IO91xk	108	59	F-120
2024-01-08 15:44	G3ZIL	14.097009	-21	0	IO90hw	2	G4HZX	IO91xk	108	59	F-120
2024-01-08 15:38	G3ZIL	14.097010	-24	0	IO90hw	2	G4HZX	IO91xk	108	59	F-120
2024-01-08 15:32	G3ZIL	14.097010	-24	0	IO90hw	2	G4HZX	IO91xk	108	59	F-120

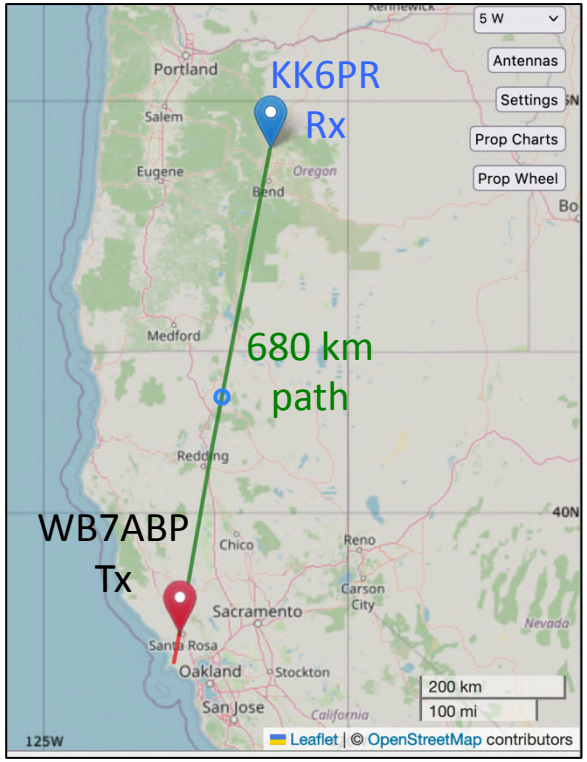
We are 108 km apart. Propagation daytime only. Might it, too, be mystery mode ‘B’? Median spread was **614 mHz**, compare with 623 mHz, 624 mHz, 578 mHz for four mystery mode B paths in the US.

Thanks to **Nigel G4HZX.**

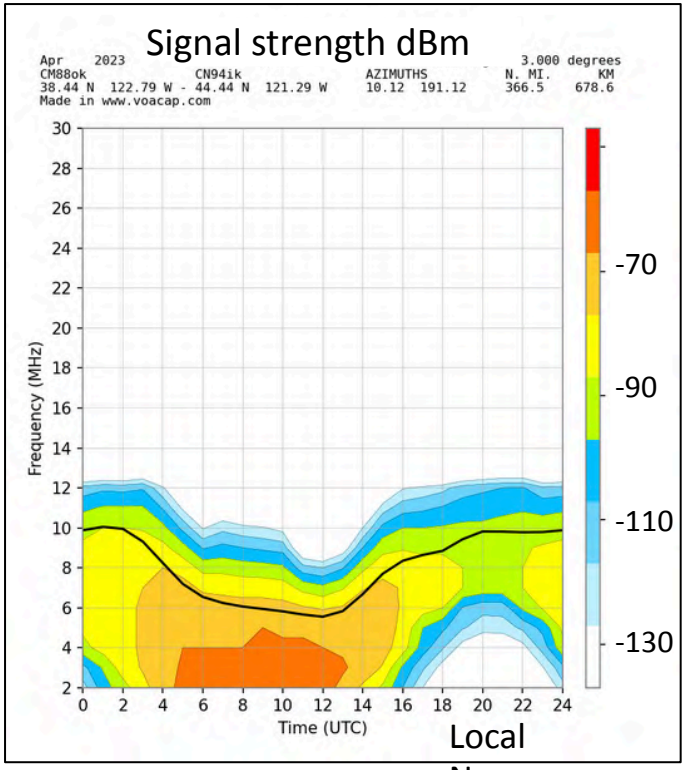
Propagation above MUF: Two-hop Sidescatter?

- Maximum usable frequency (MUF) often high enough to support daytime one-hop on 960 km path WB7ABP to KA7OEI.
- MUF drops in the evening. Sudden drop in SNR and larger frequency spread. Is this a two-hop path via scatter, e.g. from sea surface off Baja California at ~1300 km?

Let's test this idea: VOACAP propagation prediction



https://www.voacap.com/hf/

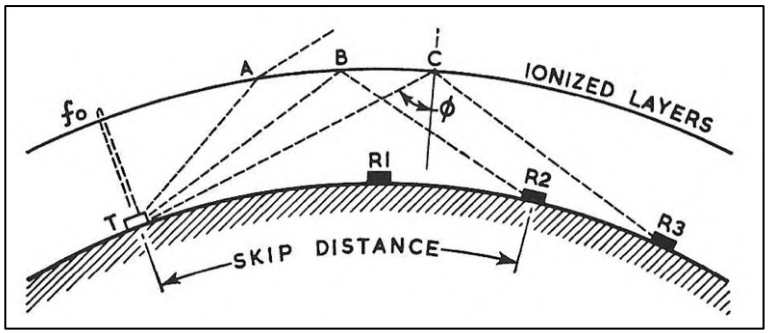


Local Noon

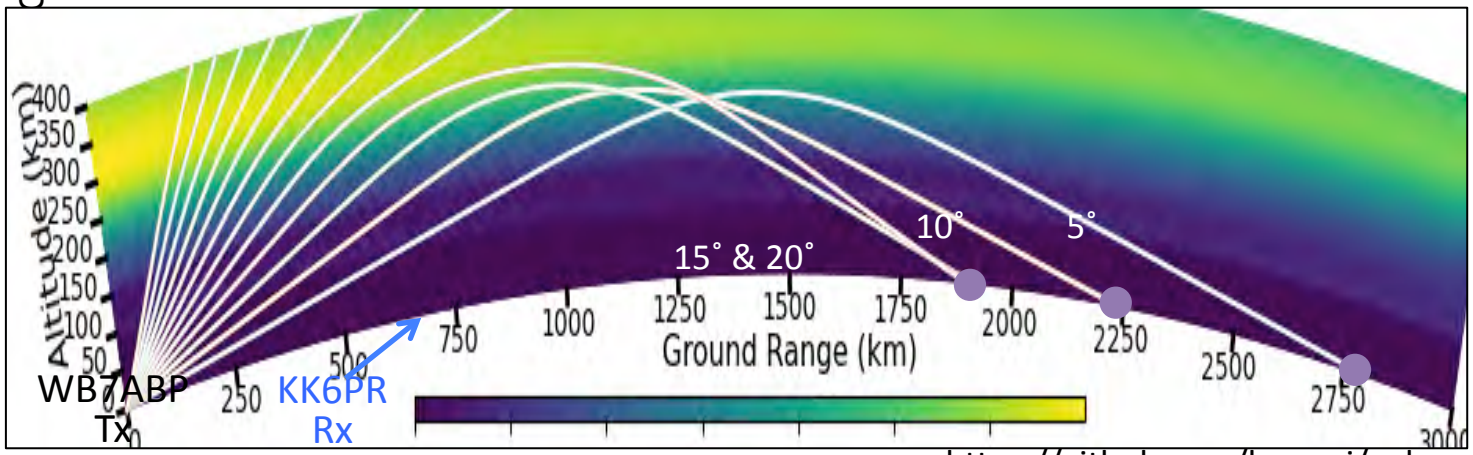
- VOACP suggests that the 10 MHz band would be open during daytime on this 680 km path in April 2023.
- *But 14 MHz very unlikely to be open.*
- Valid, *on average*, for April 2023 and a smoothed sunspot number of 68.

Reminder: Skip Distance from Ray Tracing

Courtesy RSGB Handbook



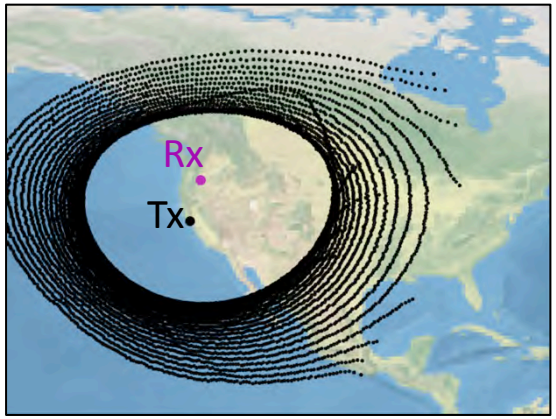
- Idea of *Skip Distance* is part of the Intermediate Exam Syllabus, sketched in RSGB Handbook.
- PyLap ray tracing lets you specify date, time, frequency, Sunspot Number, transmitter location and bearing to receiver. KK6PR is *well within* skip zone.



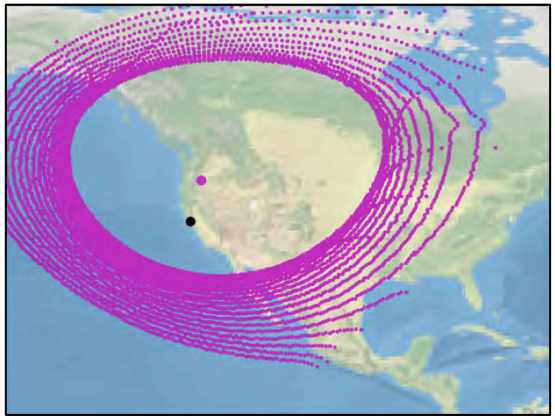
Note focus of ray landing spots at edge of skip zone.

https://github.com/hamsci/pylap

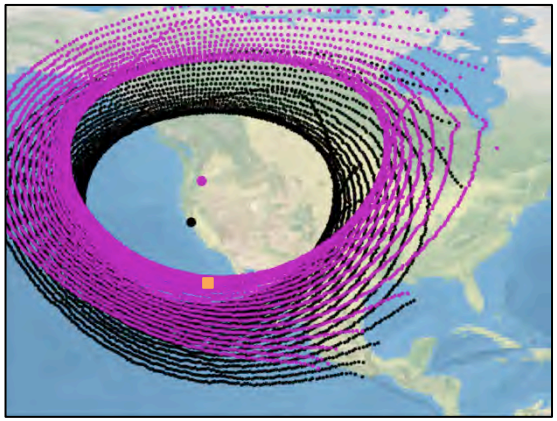
Ray tracing two-hop sidescatter



Step 1: Use PyLap ray tracing in 3D mode. Find ray landing spots from the transmitter WB7ABP. At 0400 UTC 18 April 2023 there were 7565 within 3000 km for 1˚ steps in elevation and heading.



Step 2: *In a research study the authors placed a transmitter at Step 1 landing spots to find paths to rx.* Instead I assume reciprocity to hold and place a single 'transmitter' at the receiver.



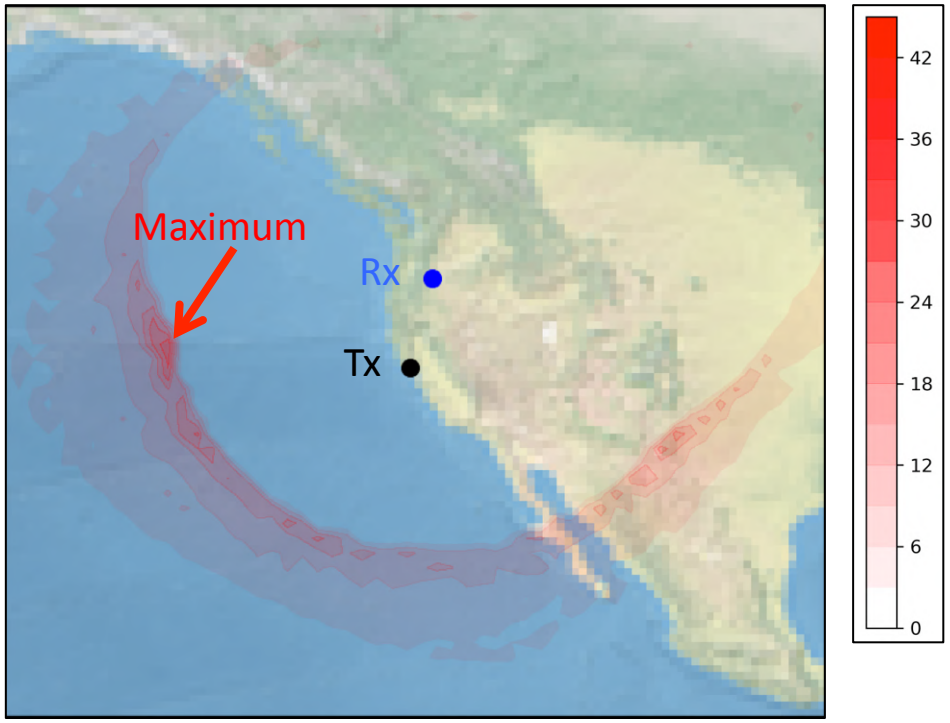
Step 3: Calculate a 'likelihood metric': for each 1˚ by 1˚ latitude/longitude box multiply the number of landings spots from tx and rx and take the square root.

Maps using Cartopy, UK Met Office. https://scitools.org.uk/cartopy/

G. Williams, 2023. Reciprocity of HF radio waves., RadCom, 99(6).

Likely areas of sidescatter from ray trace model

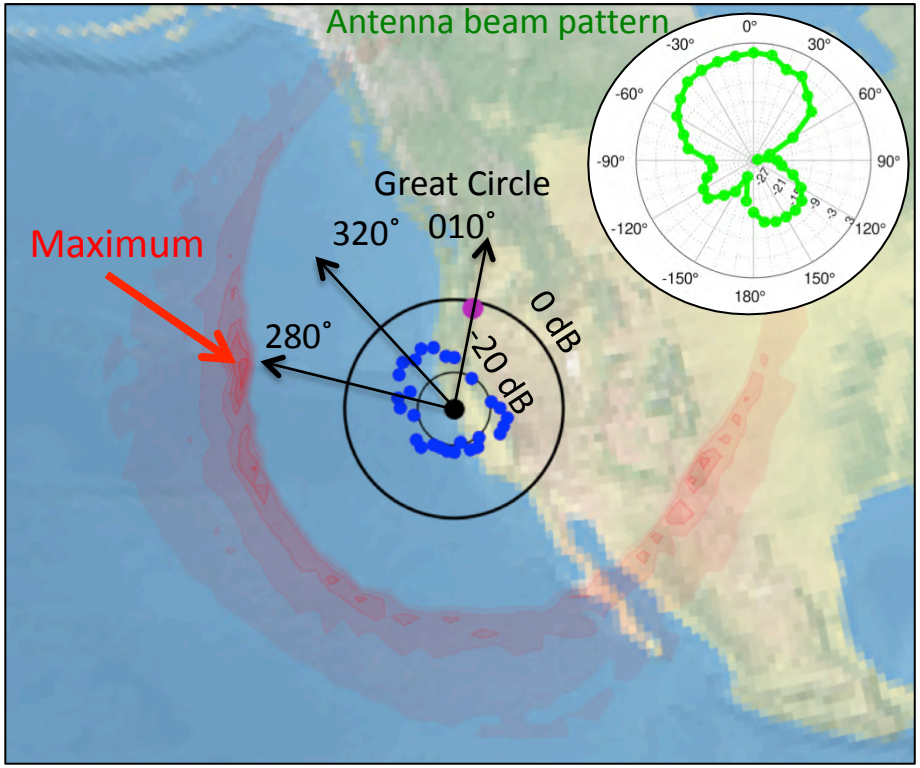
- We now have a likelihood metric in every 1˚ x 1˚ box.
- Python / Matplotlib has the *contourf* function for contouring gridded data.
- At 0400 UTC a clear single maximum, about 1500 km at heading 280˚ from the transmitter.
- Thin ring in distance is from ‘focusing effect’ of refraction seen at the edge of the skip zone.



Sidescatter likelihood on linear scale

0400 UTC 18 April 2023 14 MHz Sunspot Number: 98

Is this result credible?

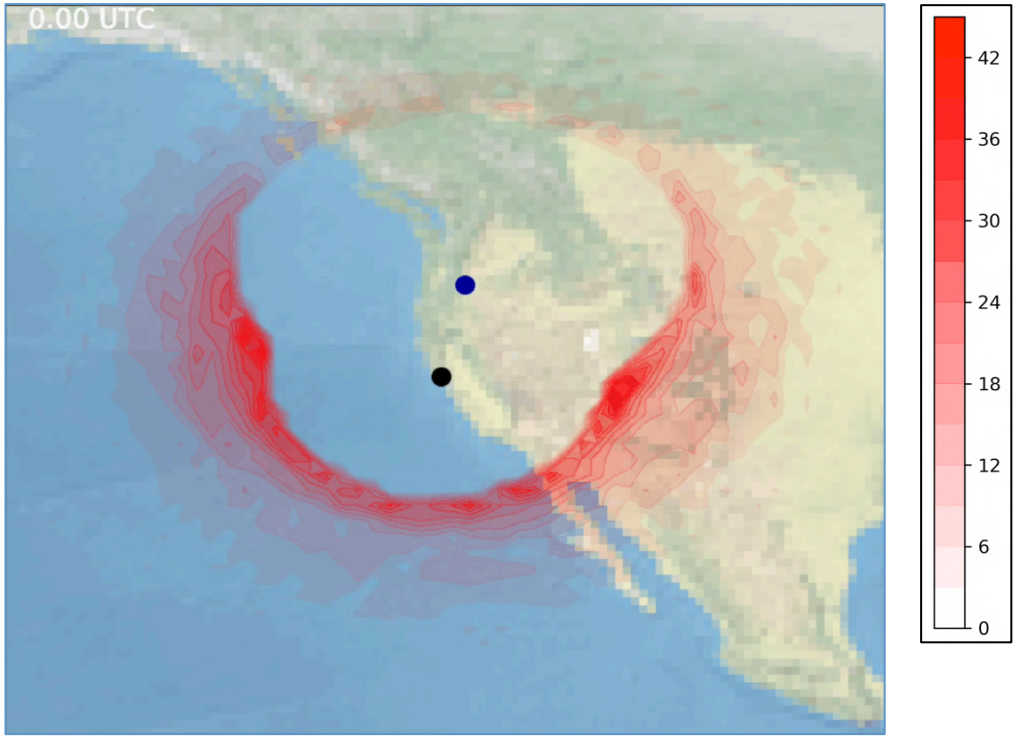


0400 UTC 18 April 2023 14 MHz Sunspot Number: 98

- 5-ele Yagi at transmit site
- For great circle propagation expect maximum at receiver if heading 010˚.
- Experiment:
  - Rotate transmit Yagi 10˚ every 4 minutes and plot SNR with heading.
  - Maximum with transmit antenna at 320˚.
  - This is 40˚ clockwise from the model-predicted area of highest sidescatter.
  - Yagi beam pattern, via surface wave, is asymmetric, biased anticlockwise.
  - So, in all, a credible agreement…

How might the area of sidescatter vary through the day?

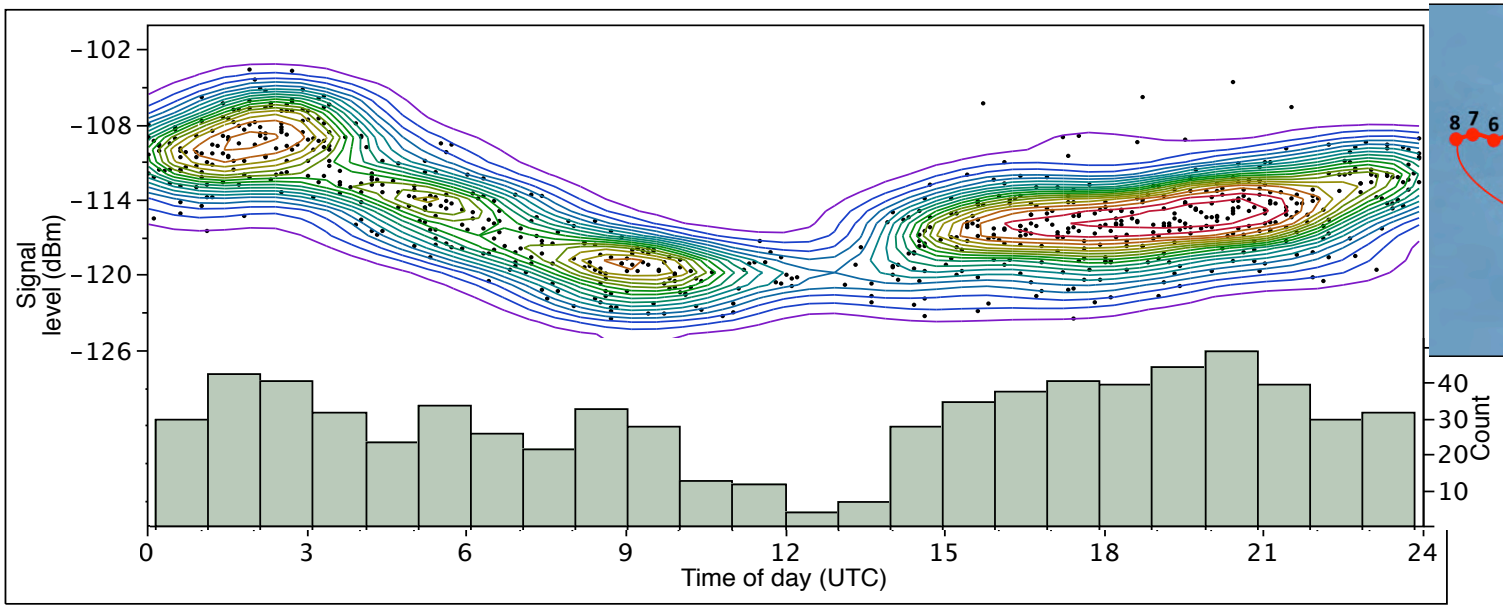
- Animation over 24 hours. Local noon is about 20:00 UTC.
- Afternoon peak to the west, weakens, moves to a greater distance, becomes an arc to the south.
- Early hours, peak forms to the east, around noon flips (perhaps to and fro) to the west.

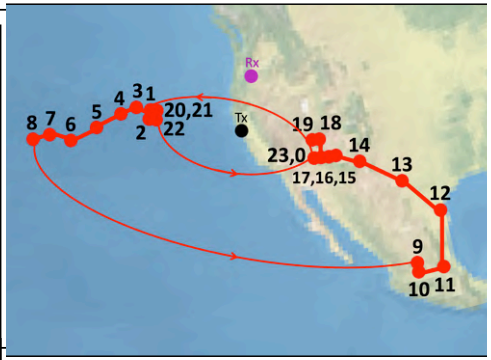


Sidescatter likelihood on linear scale

18 April 2023 14 MHz Sunspot Number: 98

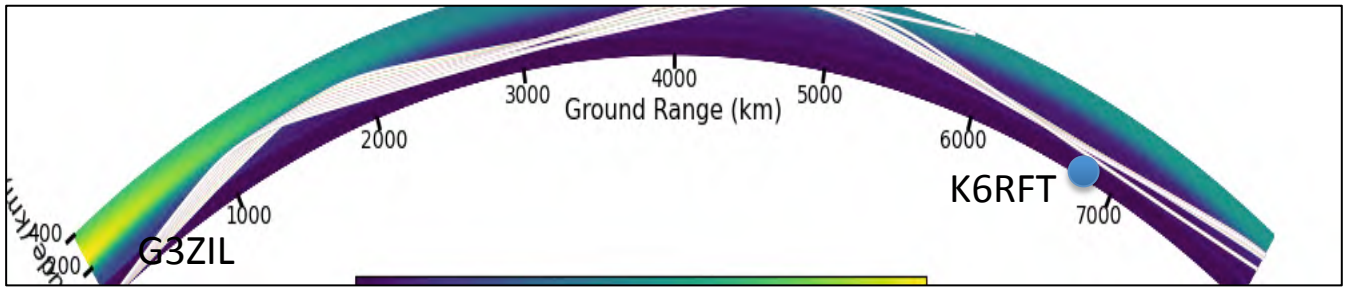
Signal level & frequency spread affect spot count

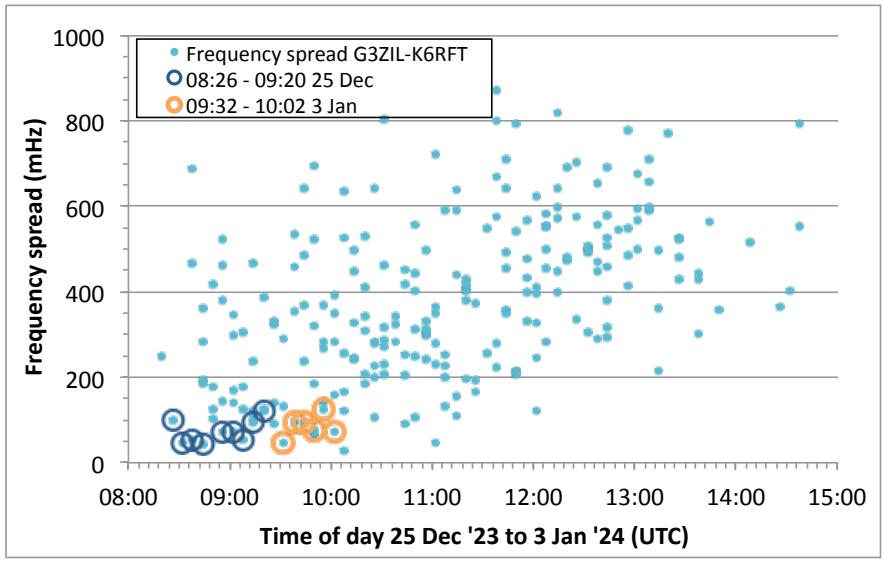




- From 09:00 to 14:00 UTC dip in number of spots from lower signal level.
- Around 22:00 UTC *suspect* dip in number of spots was because of excess spread with severe multipath returns from diametrically opposite directions from land and ocean, not low signal level.

Chordal hop on 6920 km path on 14 MHz





PyLap ray-trace simulation: sunspot number 'tuned' as 130, at 09:00 UTC 3 Jan 2024.

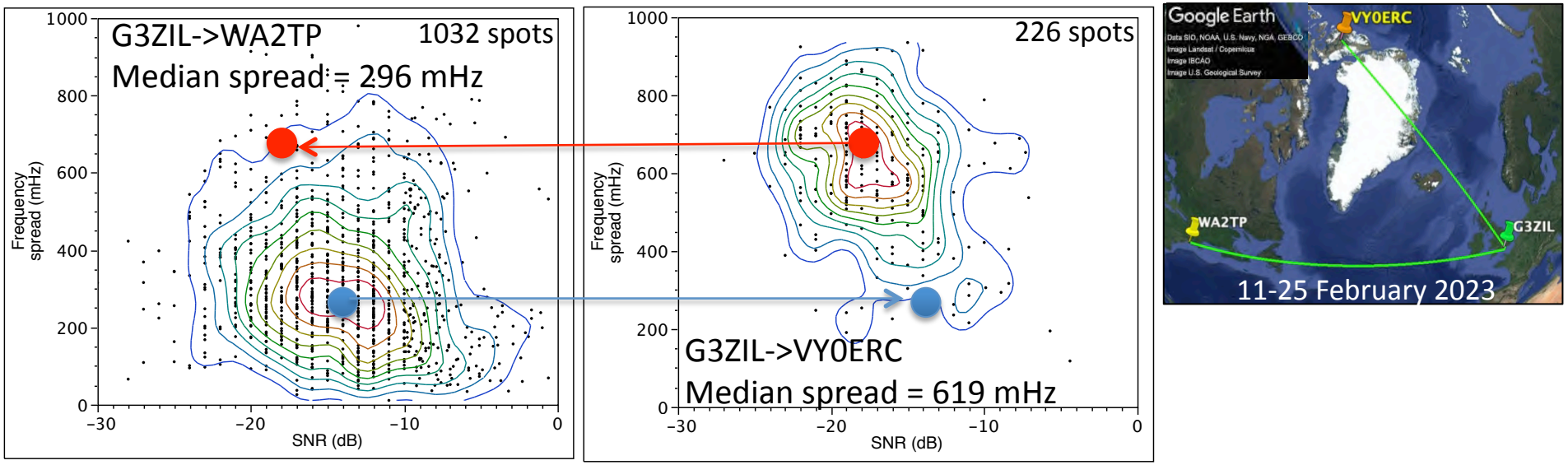
Rays at 3-10˚ take off angle do not quite reach ground.

But … this is a 'climate' model, not daily weather. All it would take is greater refraction, higher ionisation, at ~5000 km range.

Chordal hop is *not* an everyday occurrence.

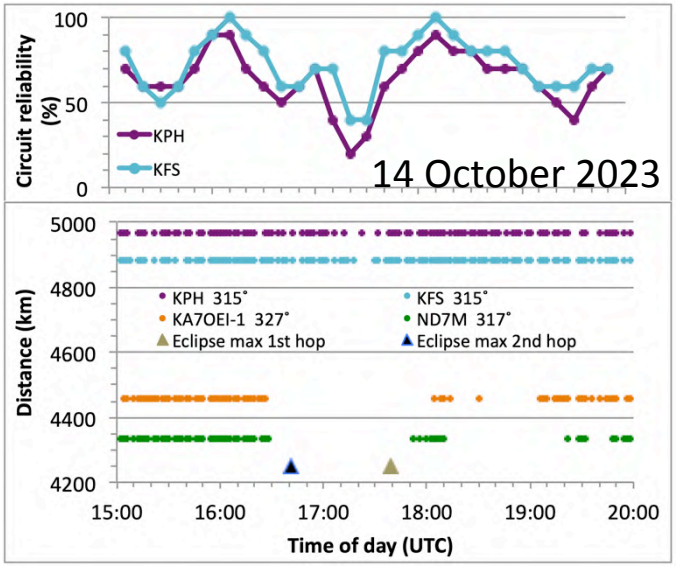
Thanks, **Peter K6RFT.**

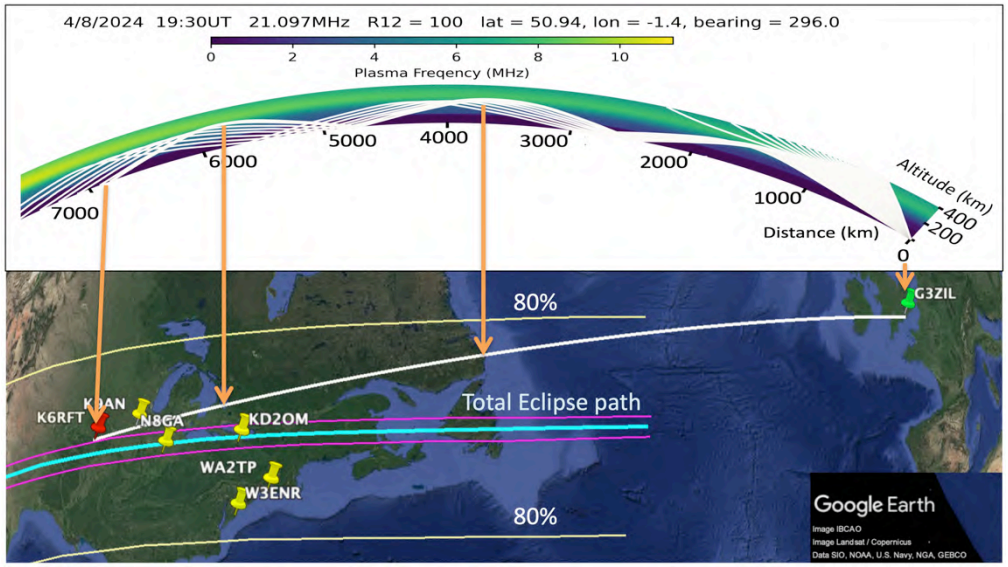
Across the Auroral Oval on 14 MHz



- Frequency spread on the path to VY0ERC double that on mid latitude path.
- Clusters hardly overlap.
- 81% of G3ZIL spots decoded at VY0ERC were with Kp 2 or less even though 2 or less only occurred 57% of the time.

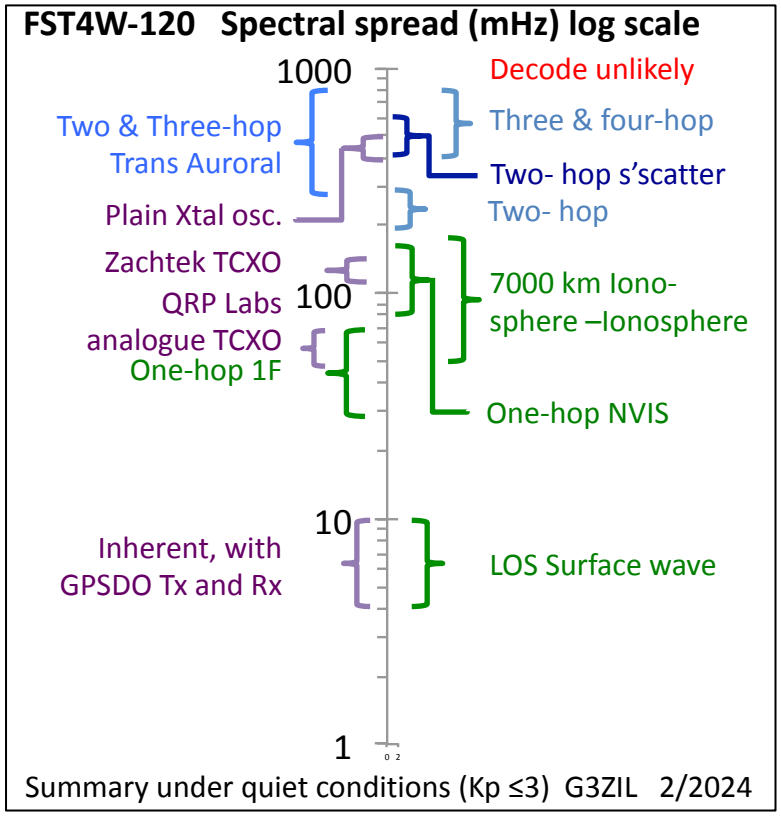
April 2024 eclipse: Opportunity for UK amateurs?





- During the October 2023 Annular eclipse over N. America two-hop paths from TI4JWC, Costa Rica to the US West Coast on 28 MHz were affected, even at 5000 km.
- **8 April 2024** total eclipse is an opportunity for effects at long range from UK stations to be observed. Effects likely at 21, 24, 28 MHz and VLF, e.g. 24 kHz NAA reception. I'd encourage WSPR transmissions on these HF bands 7-9 April.

Frequency spread ‘thermometer’ – Guide to modes



Find out more…

More on this work: http://wsprdaemon.org/technical http://wsprdaemon.org/presentations

Study of effects on propagation of the 14 October 20 eclipse:
https://youtu.be/wyYxZprR--s?feature=shared&t=1248

Above MUF modes: https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-P.2011-1-1999-PDF-E.pdf

Propagation books from RSGB:
https://www.rsgbshop.org/acatalog/Online_Catalogue_Propagation_45.html

Chen-Pang Yeang, 'Probing the Sky with Radio Waves – From Wireless Technology to the Development of Atmospheric Science'. University of Chicago Press. *Scholarly and brilliantly readable.*

Tools: https://github.com/rrobinett/wsprdaemon https://github.com/HamSCI/PyLap

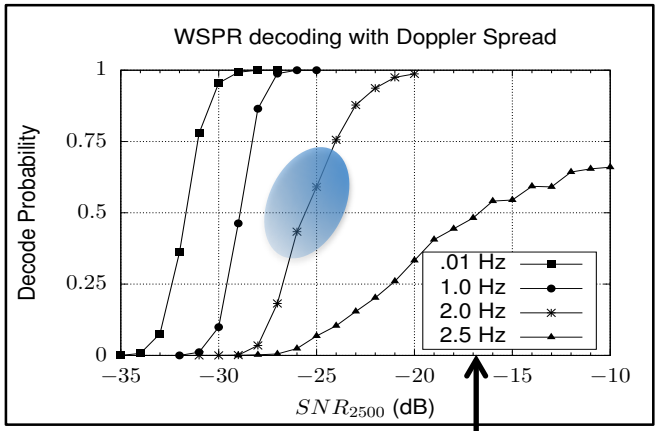
https://rsgb.org/main/technical/propagation/propagation-prediction-programs-and-forecasts/

Contact me: gwyn@autonomousanalytics.com

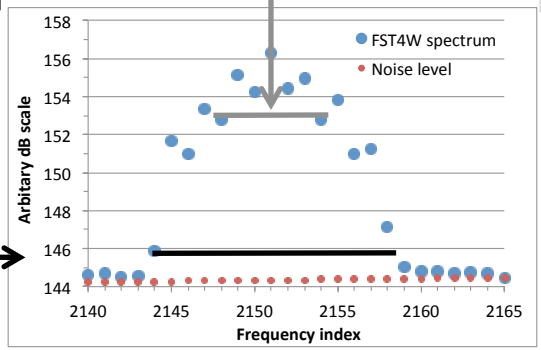
www.rsgb.org

4 Nov ’21 Spot absence: low SNR, high spread or both?

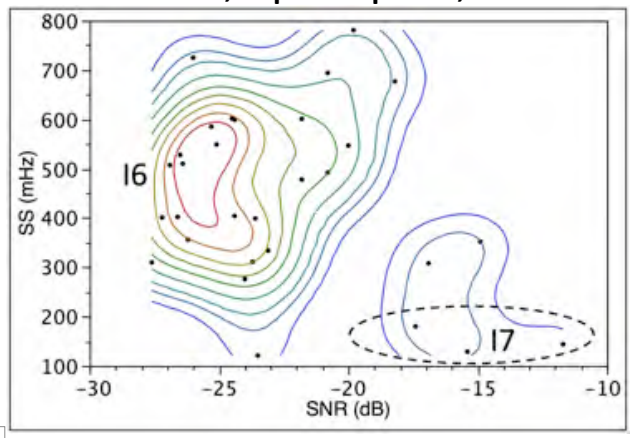
K9AN Modelled probability



At Kp=3 already in region where probability of decode about 0.5. Lower if SNR dropped or spread increased as Kp increased.



Measured at Inuvik, Kp=3 quiet, unsettled

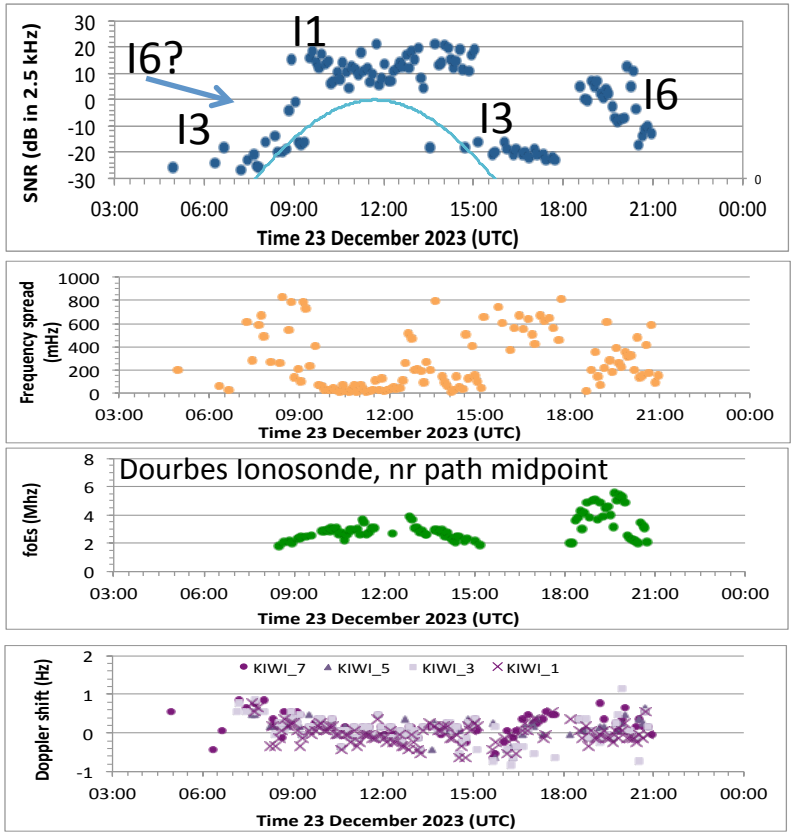


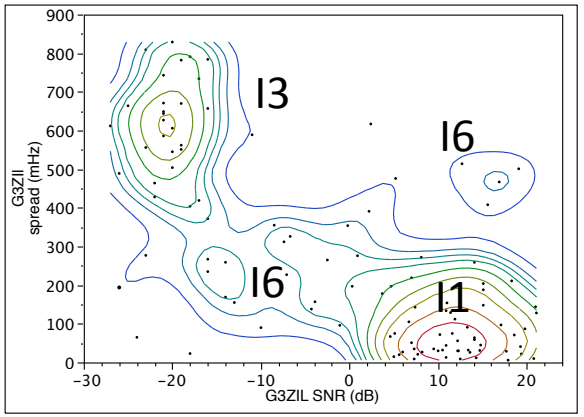
w50 50% of power

w10 is about 2.5 times w50

w10 90% of power

Not only USA… 900 km path: G3ZIL to OE9GHV





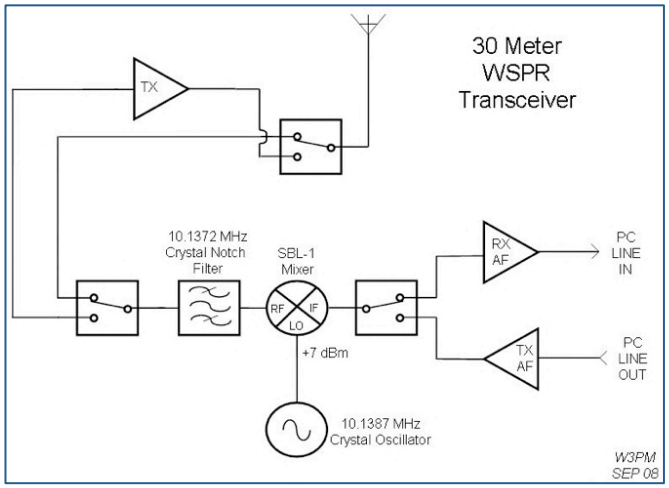
I1 one-hop F2 daytime. Median spread mHz.

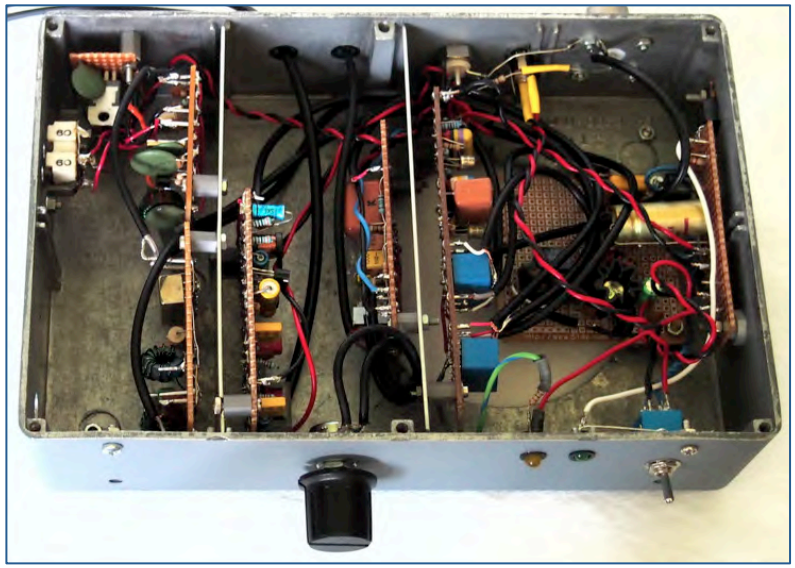
I3 two-hop sidescatter. Median spread mHz.

I6 (i.e. all except I1, I3) Sporadic E.

- QDX tx and KiwiSDR phase-locked GPS.
- F2 propagation dominated during the day even though Dourbes ionosonde showed sporadic E. Except, perhaps, for 08:50-09:02.
- I6 with certainty sporadic E, but no real clustering.
- Thanks to **Holger OE9GHV**.

Introduction to WSPR: W3PM's 30 m transceiver

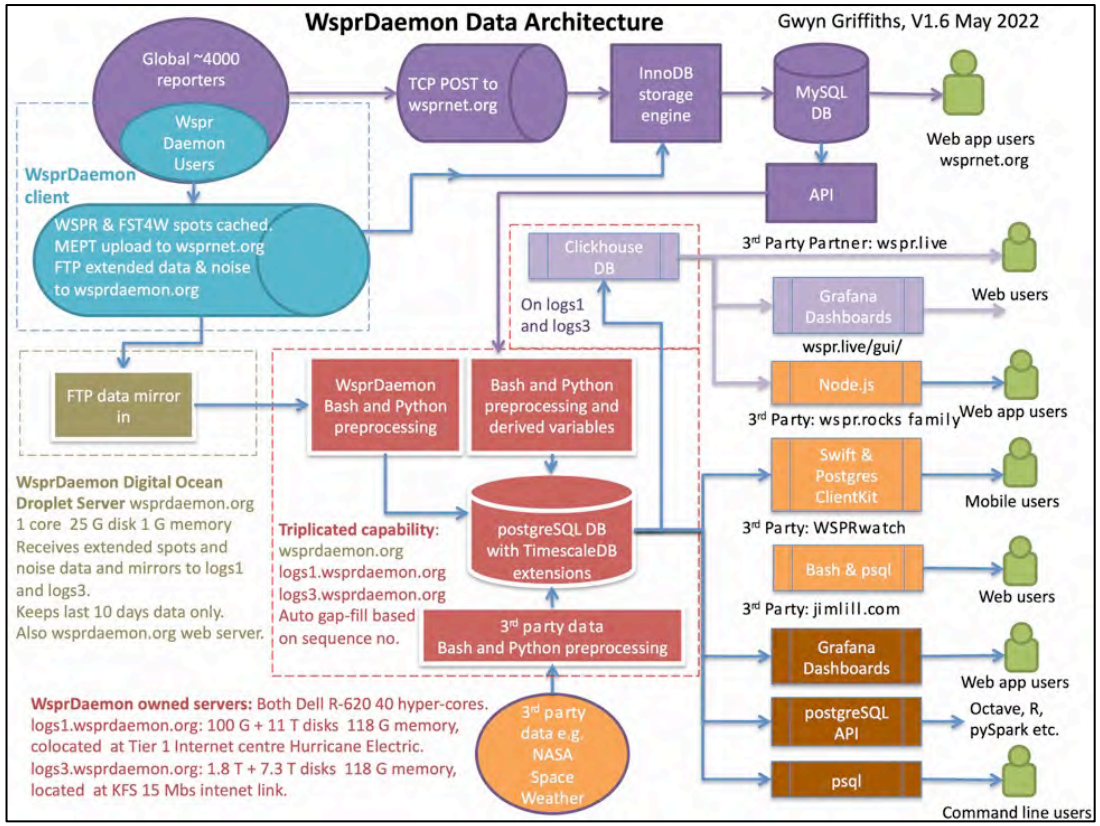


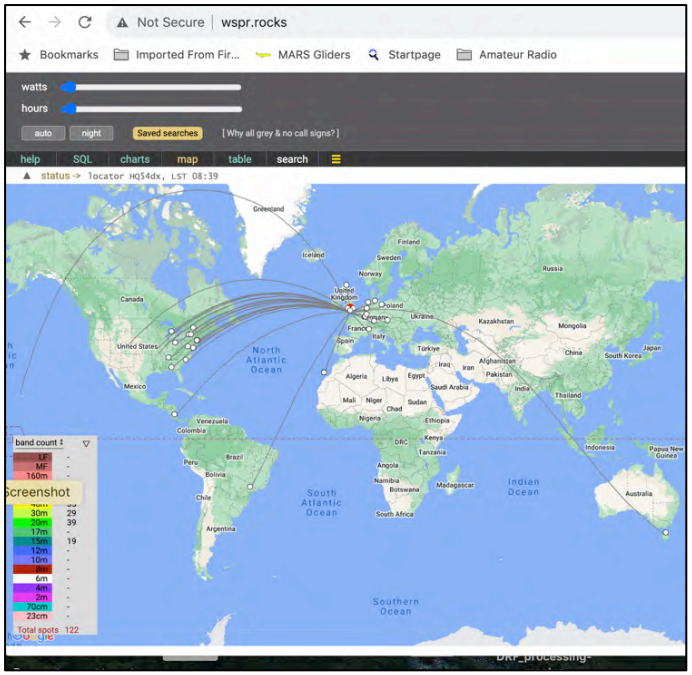


Construction on strip board in a die-cast box.
May 2015.

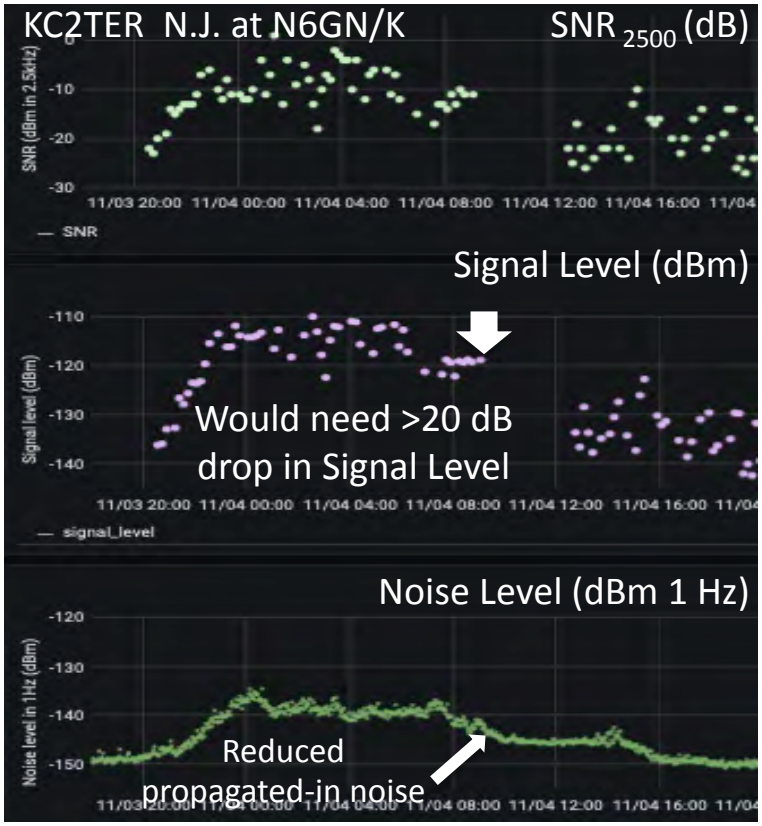
- WSJT-X with Audio in/out from PC
- Direct conversion receiver, modified for 40 m, single crystal for passband and image frequency notch
- Transmitter 1 W output from 2N4427
- *Thanks to Gene Marcus W3PM*

WsprDaemon: Open access or via apps e.g. wspr.rocks





FST4W HF Propagation studies: The journey starts…



- Talk at the HamSci conference, March 2022, "*Effects of the 3–5 November 2021 Geomagnetic Storm on Reception in Colorado of WSPR transmissions...*"
- Was this cliff edge in decoding spots from New Jersey to **Glenn N6GN** Colorado on 7 MHz due to:

  a) Over 20 dB drop in SNR
  b) Excessive Doppler spread
  c) Both of the above.
- What is 'Excessive Doppler spread'?

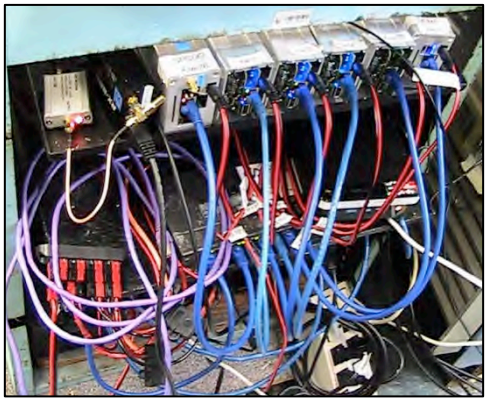
Example on online graphs from WsprDaemon including noise and signal levels as well as SNR

Serendipity: Finding a welcome and more

Coffee Catz, Sebastopol, Sonoma County, Northern California.

N6GN, AI6VN, K6PZB, K6RFT, KJ6MKI, KK6EEW, KP4MD/W6, N3AGE, W6SB, WA6UAT, WB6CXC, WB6YRW, WW6D, WA7ABP, W7WKR

Maritime Radio Station KPH receive site, Point Reyes, Marin County, Northern California. Cared for by the Maritime Radio Historical Society.



Rack of KiwiSDRs at KPH installed and maintained by AI6VN *et al*. Images courtesy KP4MD/W6.

WsprDaemon: The enabler for my results to come

- An initiative and creation of **Rob Robinett, AI6VN**
- Robust decoding and reporting of WSPR and FST4W spots from multi-band KiwiSDR and RX888 receivers.
- Own database with open access:
  - Additional variables and greater precision compared with wsprnet.org
  - Greater resilience, triplicated servers on different sites.
  - ‘SQL’ access to WSPR spots since 2008

http://wsprdaemon.org