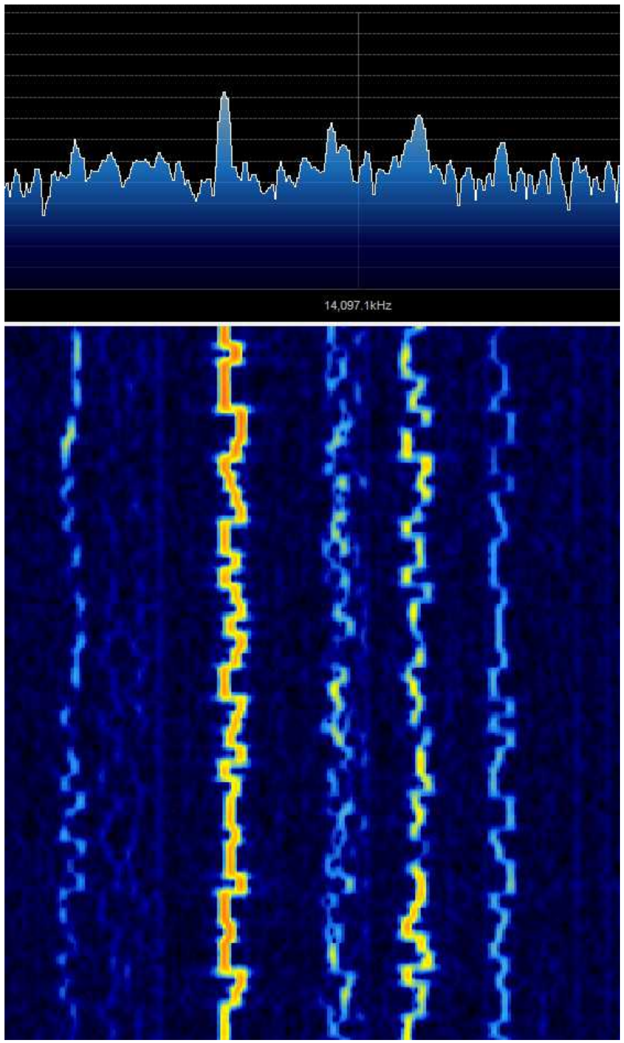
WSPR
And Related Ham Projects

- Raspberry Pi transmitter, still running 24/7 since December 2015
- Other WSPR transmitter designs
- WSPR being used for (very limited) telemetry
- A drift-buoy project
- Test equipment and breadboarding

Weak Signal Propagation Reporter

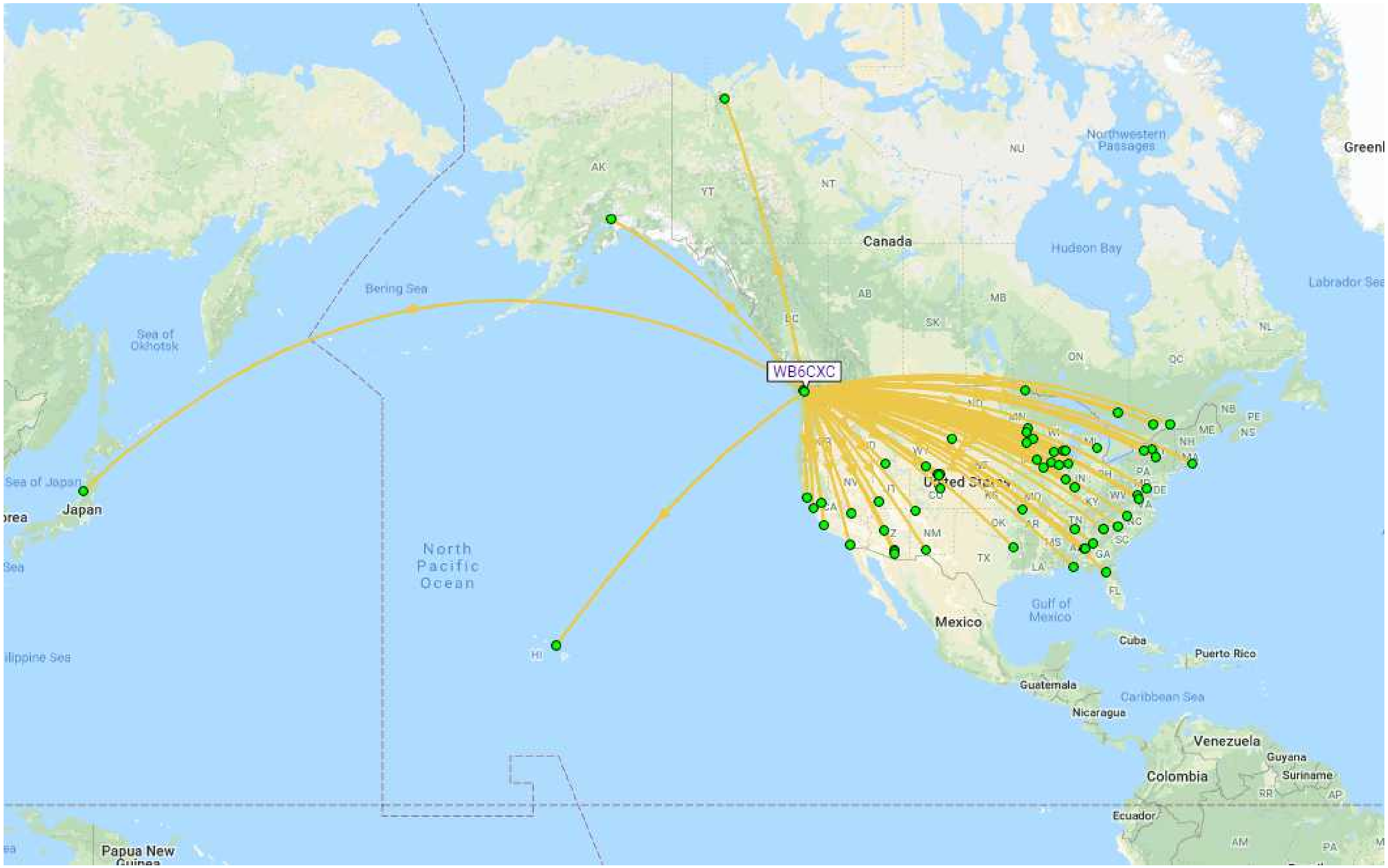
- Worldwide: **1000** reporting stations, **1500** transmitting stations
- Operating on USB dial (MHz): 0.136, 0.4742, 1.8366, **3.5686**, 5.2872, 7.0386, 10.1387, 14.0956, 18.1046, 21.0946, 24.9246, 28.1246, 50.293, 70.091, 144.489, 432.300, 1296.500
- Message: Callsign, 4-digit locator, power level in dBm: 50 bits
  - After Forward Error Correction = 162 bits
  - Plus a 162-bit synch pattern = 324 bits
- Modulation
  - 4-FSK (2 bits / symbol)
  - 1.4648 Hz tone separation, 1.4648 Baud
- Duration of transmission: 110.6 seconds
- Transmissions start on even UTC minutes

Modulation Detail



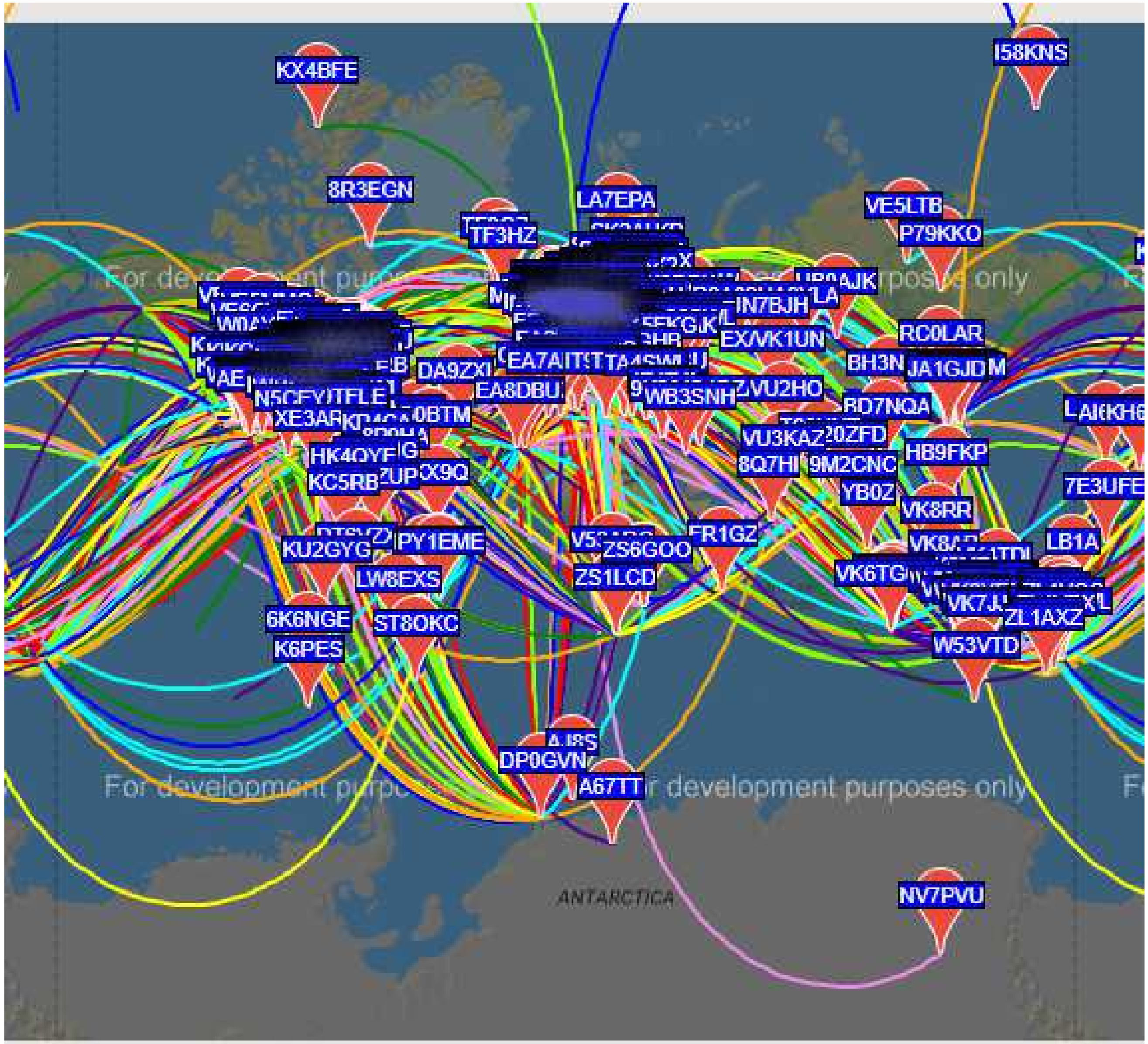
- Multiple transmitters share a common 200 Hz-wide band
- There is no frequency assignment, so interference can occur
- People (or radios) randomize their frequency, pick timeslots, repetition rates to reduce collisions
- Very clever use of DSP to decode “hidden” signals
- We can see the four-level FSK modulation
  - 1.4648 Hz tone separation
  - 1.4648 Hz Baud (2.9296 bits/second)

20-Meter WSPR

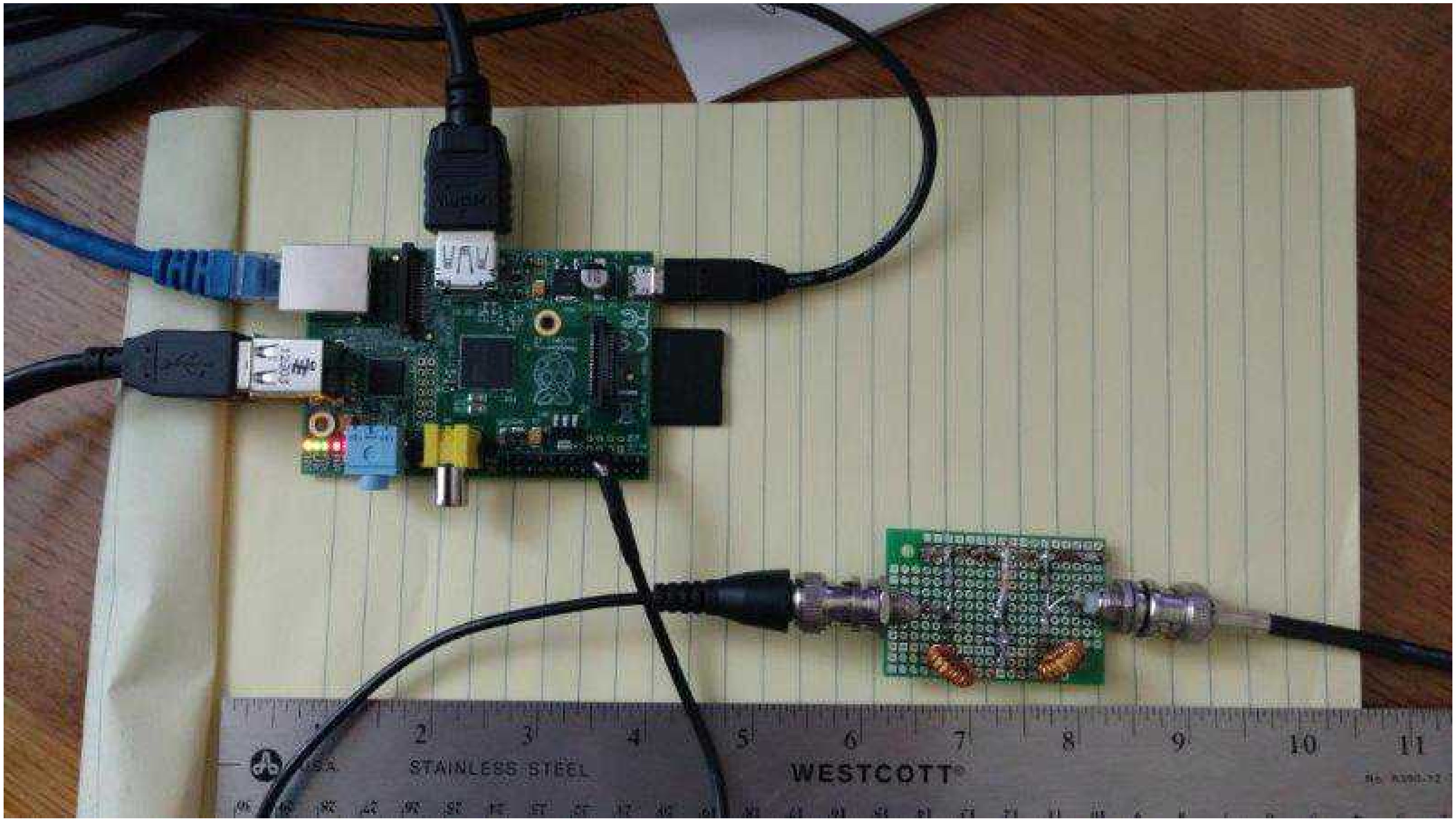


- 5055 miles with 10mW – Friday Harbor to French Guiana
- 690 Miles with 0.1mW – Friday Harbor to Santa Rosa

20-Meter WSPR, 24 Hours



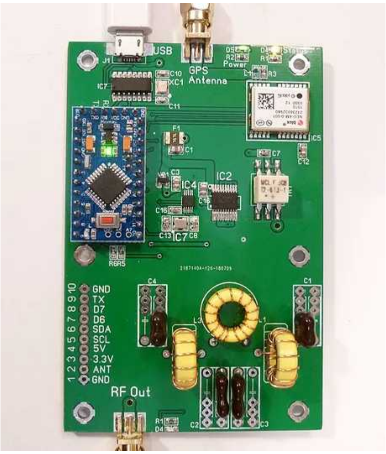
Raspberry Pi Transmitter, still running 24/7 since December 2015



Other WSPR transmitter designs

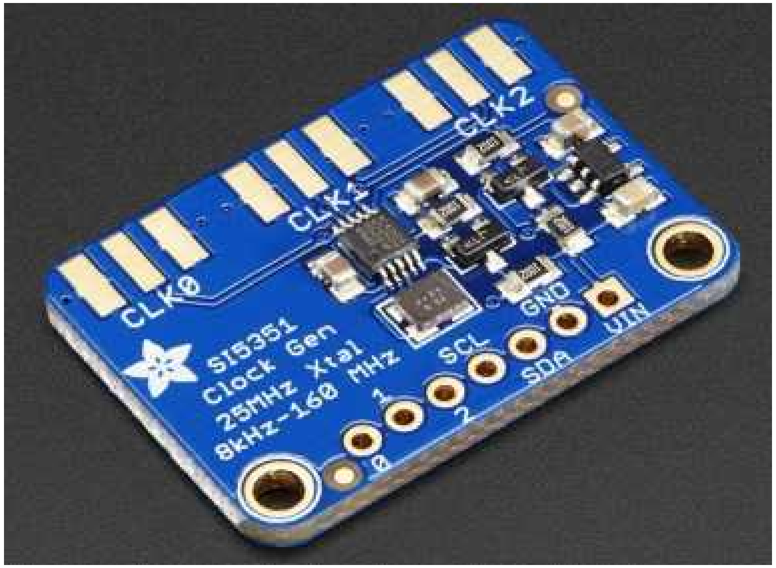
- QRP Labs "Ultimate 3S" kit -- $33

- ZachTek "WSPR-TX_LP1" -- $76



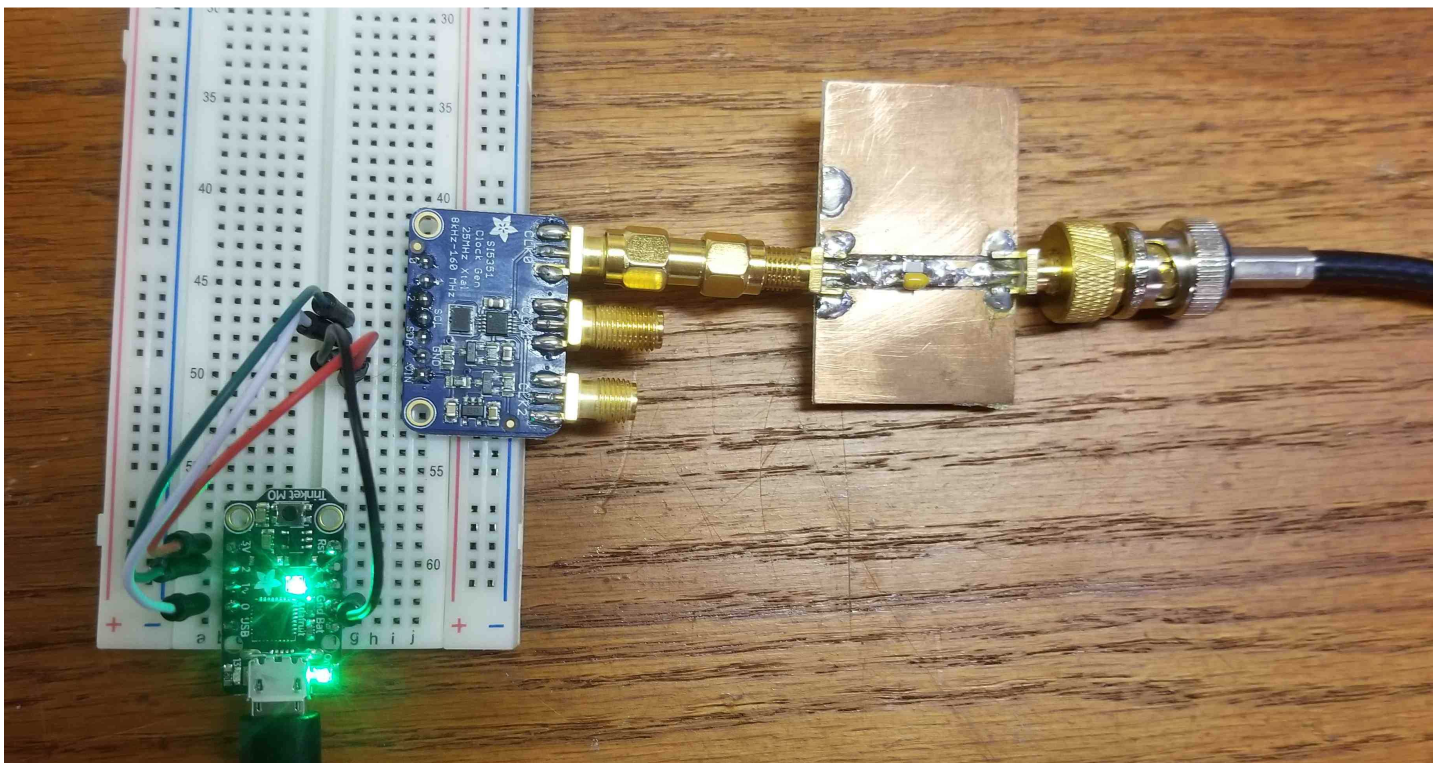
WSPR Transmitter Designs

- SI5351 Clock Generator, 8 Khz – 160 MHz, $8 from Adafruit



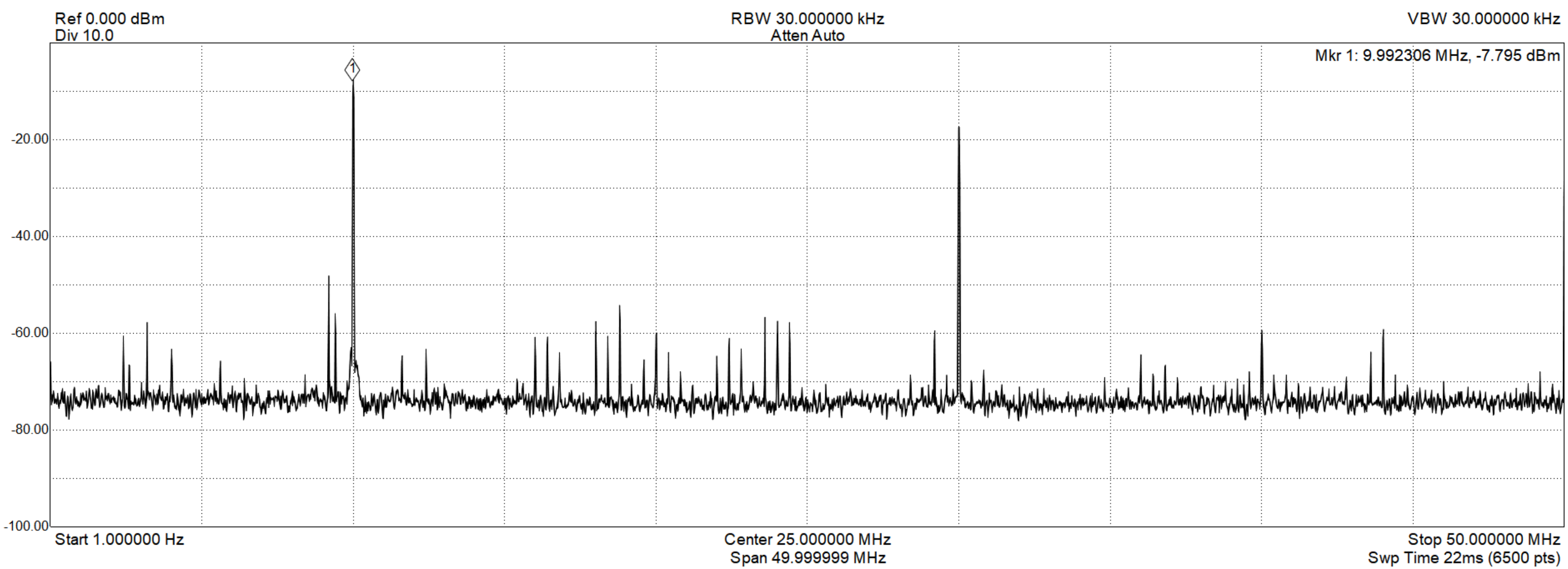
Clock Generator Testing

- SI5351 Clock Generator and an Adafruit “Trinket MO” Arduino, running Python.
  - Cheap and easy(Trinket is $8.95) Not a lot of memory.



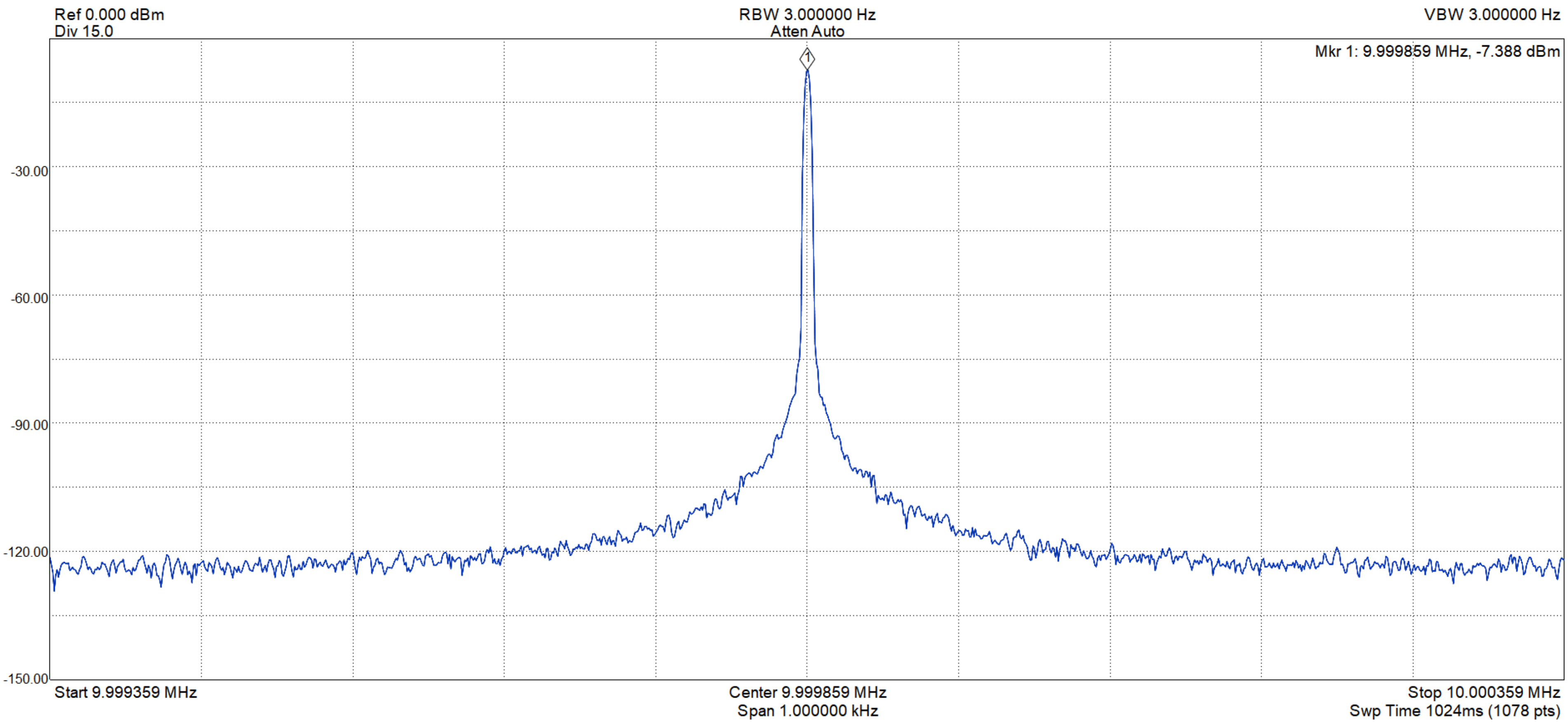
SI5351 Clock Generator

- A pretty nice output, will clean up nicely with simple filter



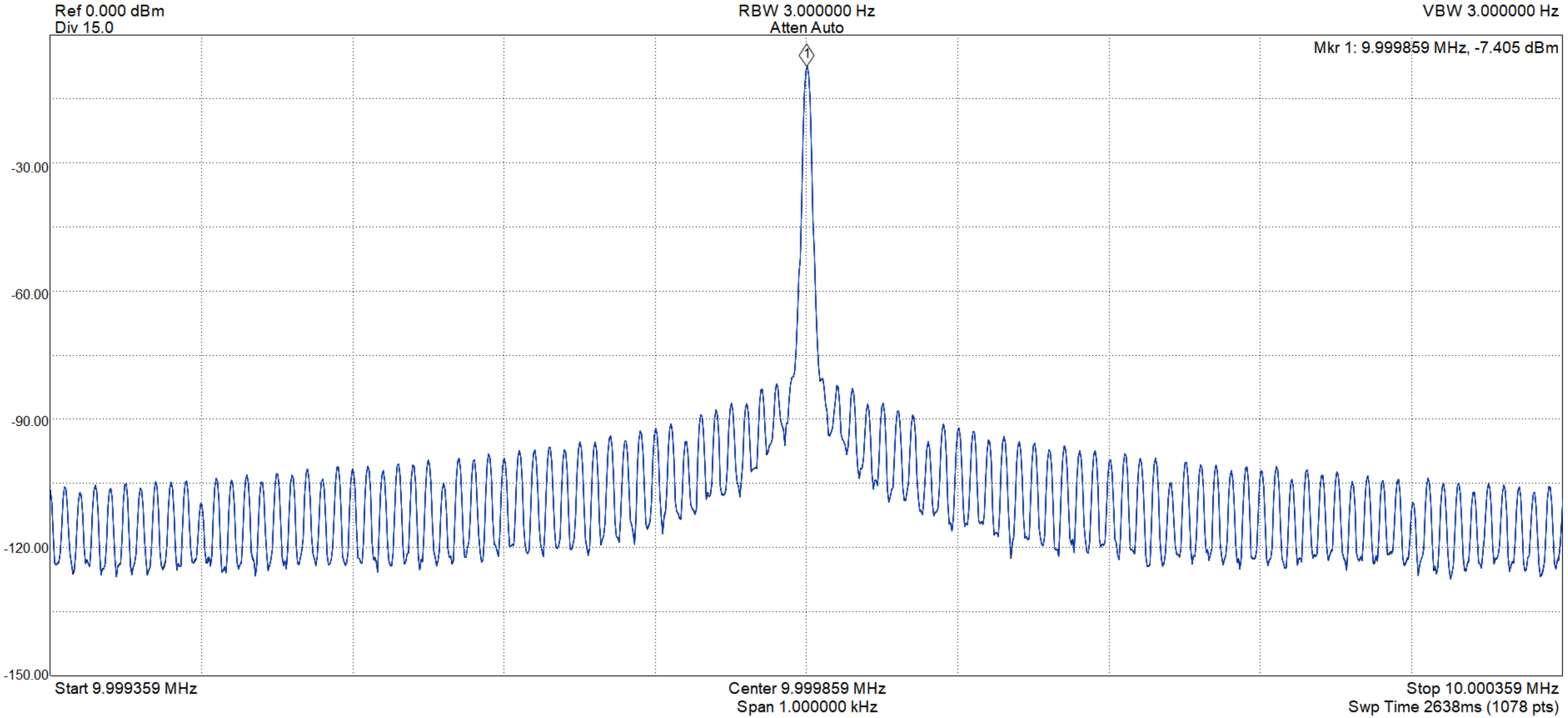
SI5351 Clock Generator

- Using integer dividers gives clean output (close-in)



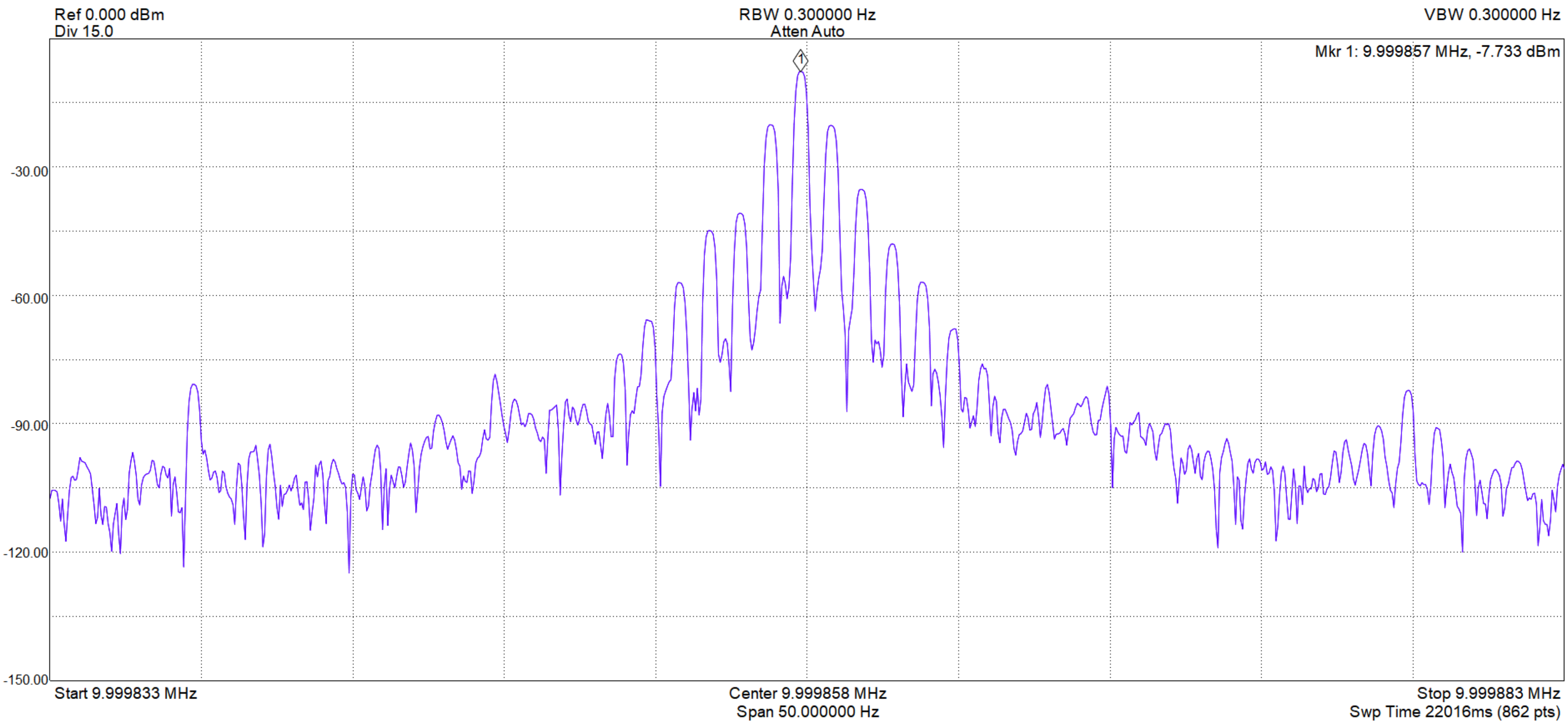
SI5351 Clock Generator

- Using fractional dividers adds spurs (close-in)
- These are interesting, but unlikely to cause actual problems



SI5351 Clock Generator

- Using fractional dividers adds spurs (very close-in: 5Hz/div)



Balloons and Drift Buoys

- Balloon transmitters circle the planet
  - http://qrp-labs.com/ultimate3/ve3kcl-balloons.html
- Some drift buoys too
  - https://www.qsl.net/zl1rs/oceanfloater1.html
- Ocean Voyager project
  - http://www.jrfarc.org/hf-voyager

Ham Telemetry

- APRS
  - Ability to encode significant amount of data
  - Cloud database access
  - 300 baud FSK, AX.25
  - Non-robust coding, no FEC (FX.25 may add FEC?)
  - Pretty good VHF coverage
    - but not useful for the middle of the ocean
  - Very few HF receiving sites
    - 10 MHz, some using PSK31, 31 bits/second, no FEC

Ham Telemetry

- WSPR
  - Worldwide receiving network and centralized WSPRnet database
  - Some data fields re-purposed for telemetry. A bit of a kludge but used for balloons and supported by WSPRnet. *Very* limited data capacity.
- FT8, JT9
- JS8CALL (AKA FT8CALL)
  - allows free-form text messages
- Satellite: Iridium, Ham

WSPR Telemetry

- Basic WSPR packet: [**Callsign**, **Grid**, **Power** in dBm]
  - Example: WB6CXC CN88LN 10
- Balloons re-use **Power** field for coarse altitude in standard packet
- Second packet uses invalid callsigns, same grid
  - “telemetry flag” and 20 transmitter I.D. values
- Remaining callsign field and other fields give about 23 bits for data
- For more detail, see http://hojoham.blogspot.com/2016/03/wisp1-telemetry.html

A Drift-Buoy Project

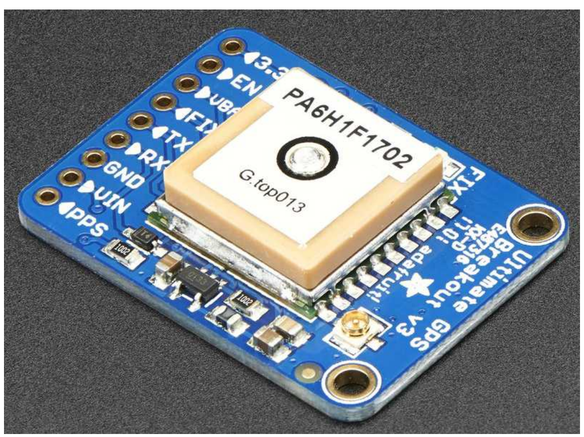
- Solar-powered buoy, set free to drift with the currents.
- Small, cheap, fun
- Call home with data:
  - Position
  - Temperature
  - Wave data (using 6-axis accelerometer / gyro)
  - Windspeed, direction (using wind/antenna tilt and fluxgate)
  - Status (battery, solar)

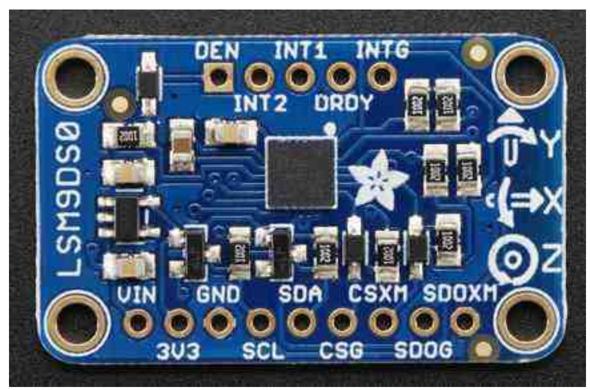
Drift-Buoy Challenges

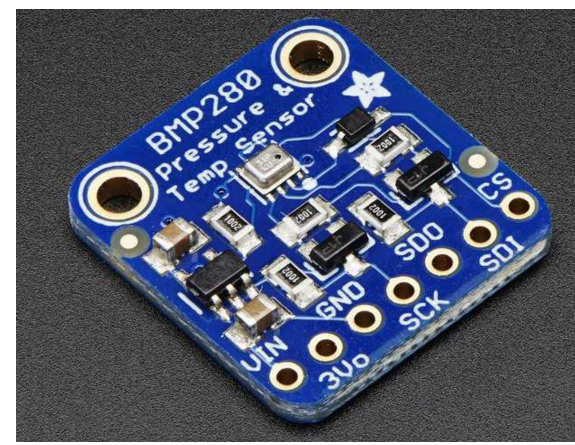
- Power consumption
  - Arduino, GPS, Sensors
  - Efficient transmitter
  - Solar panel
- Communications modes
- Short antenna
- Flotation
- Waterproof
- Programming

Sensors

- Adafruit “Ultimate GPS Breakout” - $39.95
- Adafruit 9-DOF Accel / Gyro / Magnetometer - $14.95
- Adafruit Barometric Pressure + Temperature - $9.95
- Similar items available from Sparkfun, China





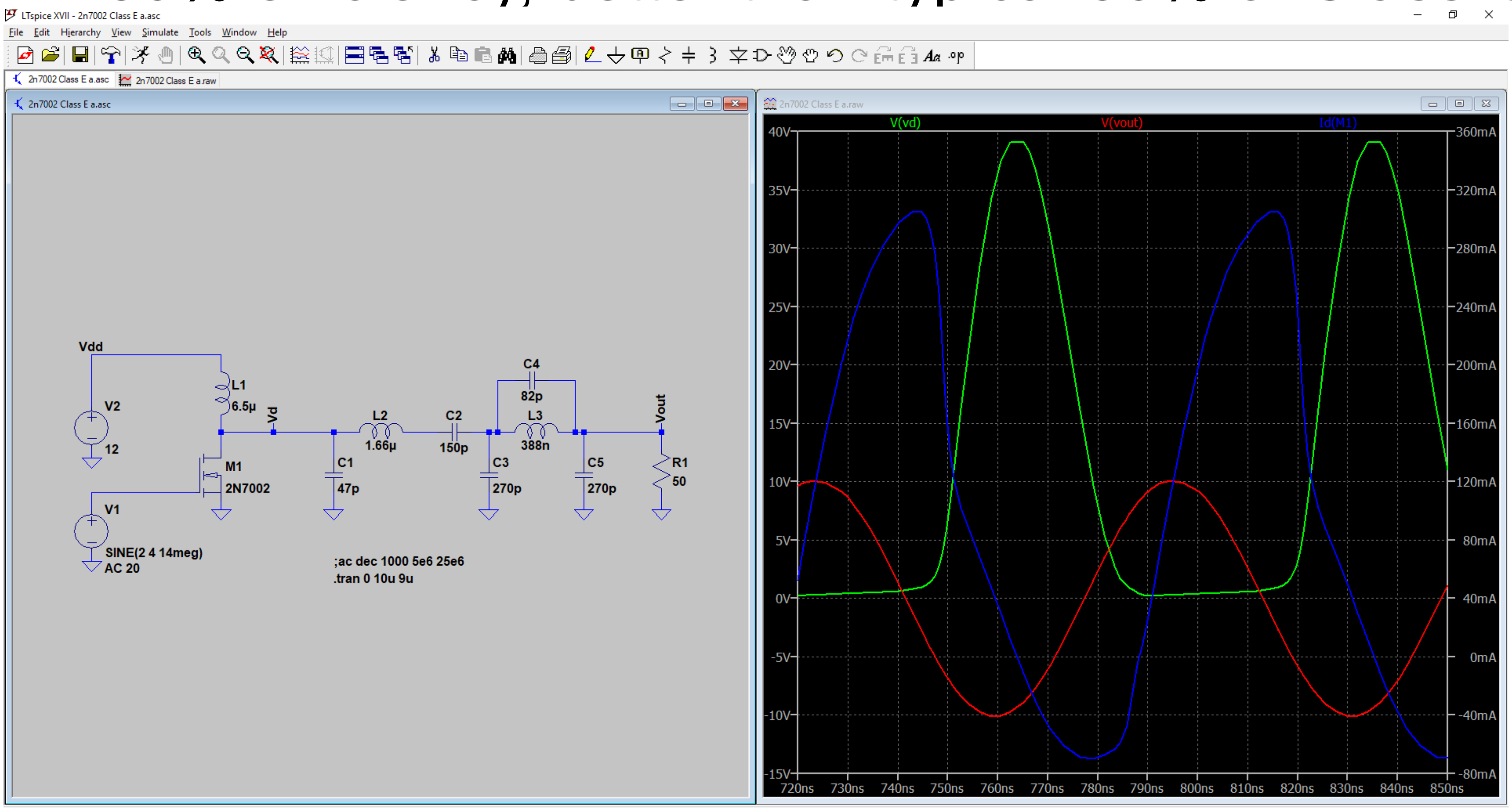


Short Vertical Antenna

- 102” whip is 0.086 wavelength at 10 MHz
- Very low radiation resistance, small series capacitance
- **2.9 Ohms radiation resistance**
- 16pF series capacitance, needs 16uH loading coil
  - (or 25pF / 10uH – depending on which equations)
- Good news: excellent seawater ground
- Bad news: very high Q loading coil required
  - Q of 50 adds 13dB additional loss (ideal ground)
  - Q becomes less critical with larger ground losses

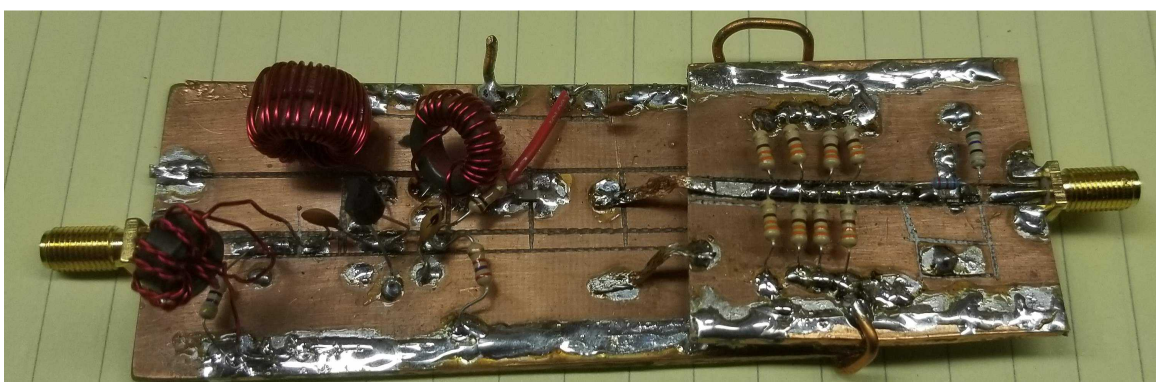
Drift-Buoy Transmitter

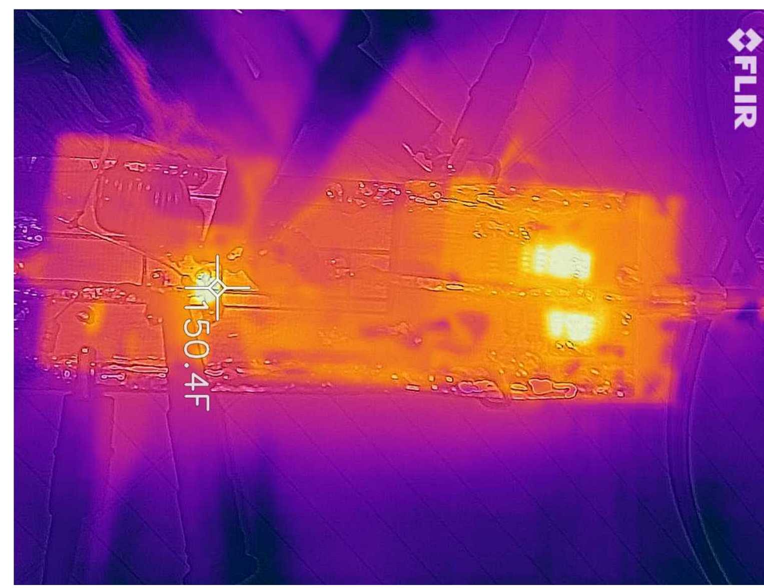
- Class-E output stage, 1W, 10 MHz
  - 80% efficiency, better than typical 50% of Class-C



Drift-Buoy Transmitter

- Breadboard Class-E output stage, 1.5W, 10 MHz
  - Thermal image confirms TO-92 transistor dissipating about 150mW (thermal resistance calculation)
  - Dummy load resistors burning around 1.5W





Test Equipment

Test Equipment

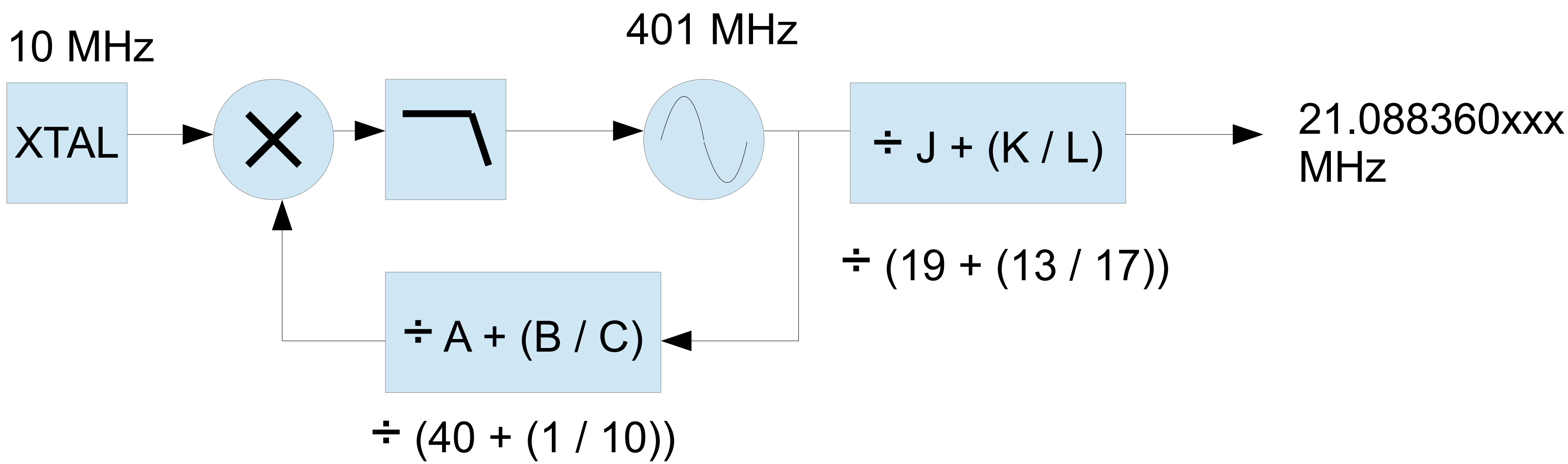
- Power supply, DVM
- Oscilloscope
- Signal generator
- Spectrum analyzer, tracking generator, directional coupler
- Antenna analyzer (Bluetooth)
- Dummy loads, attenuators, cables, adaptors (N, BNC, SMA)
- Receivers (ham, SDR)
- Precision 10MHz reference (OCXO, Rubidium, GPS-disciplined)

Breadboarding

- Woodcarving “V-Tool” gouge used to carve copper lands on PCB
- Clamps and steel rule for straighter lines and less blood-loss
- Copper foil for low-Z paths

- Chinese SMA connectors are $1 ea.

Si5351 Clock Synthesizer



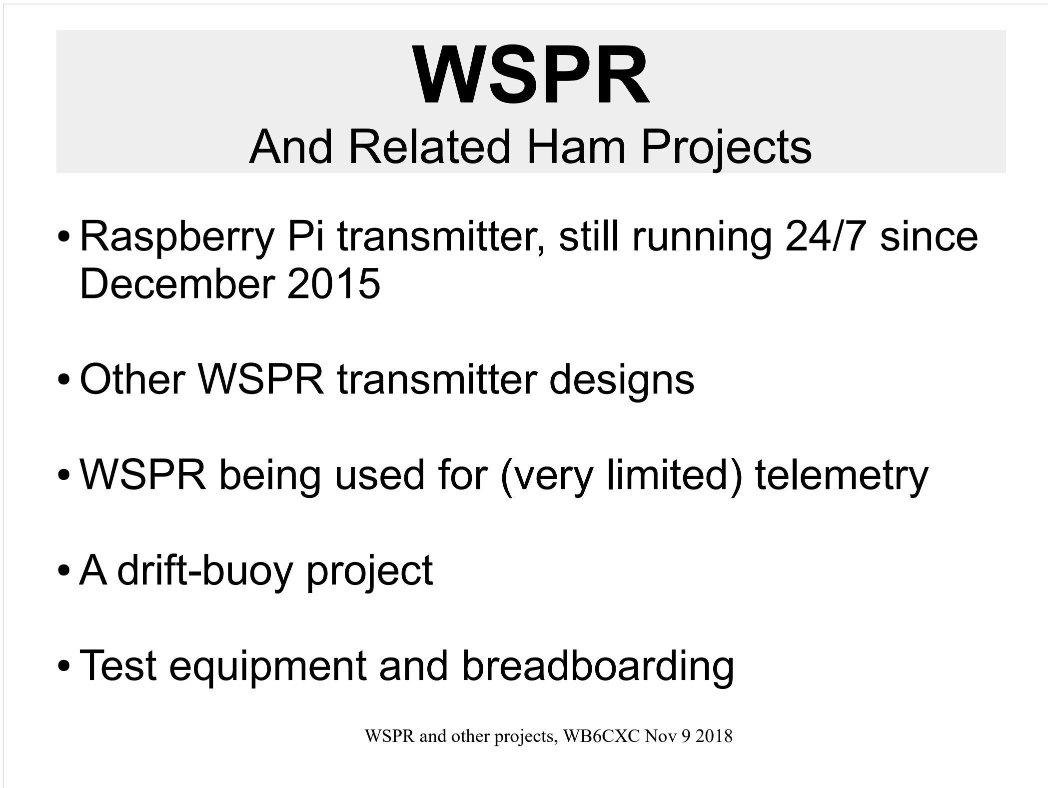
The divider values here are chosen to illustrate the flexibility of fractional division in both the PLL feedback loop and the output paths.

Links

- Previous WSPR Presentation: http://wb6cxc.com/?page_id=65
- WSJT-X: https://physics.princeton.edu/pulsar/k1jt/wsjtx.html
- WSPRnet: http://wsprnet.org
- WSPR Telemetry: http://hojoham.blogspot.com/2016/03/wisp1-telemetry.html
- WSPR on Pi: https://github.com/JamesP6000/WsprryPi
- Balloons: http://qrp-labs.com/ultimate3/ve3kcl-balloons.html
- Drift buoys: https://www.qsl.net/zl1rs/oceanfloater1.html
- QRP Labs: https://www.qrp-labs.com/ultimate3
- Moetronix WSPR beacon: http://moetronix.com/wspr.html
- ZachTech: https://www.zachtek.com

Links

- Adafruit: https://www.adafruit.com/product/2045
- Sparkfun: https://www.sparkfun.com/products/13339
- Class E Amplifier:
  - http://people.physics.anu.edu.au/~dxt103/160m/class_E_amplifier_design.pdf
  - http://www.norcalqrp.org/files/Class_E_Amplifiers.pdf
- Short vertical antenna:
  - https://www.qsl.net/l/lu7did/docs/QRPp/09.pdf
  - http://people.physics.anu.edu.au/~dxt103/calculators/Rrad.php
  - http://www.strobbe.eu/on7yd/136ant/#ShortMonopole



Back at the end of 2015 I gave a presentation on WSPR, and how a WSPR transmitter could be built from a Raspberry Pi – with no other active components. That presentation contained technical details of the digital synthesis of the WSPR transmit signal, as well as some options for WSPR reception.

This presentation touches on some of the same topics, as well as describing the design-in-process of a WSPR drift-buoy.

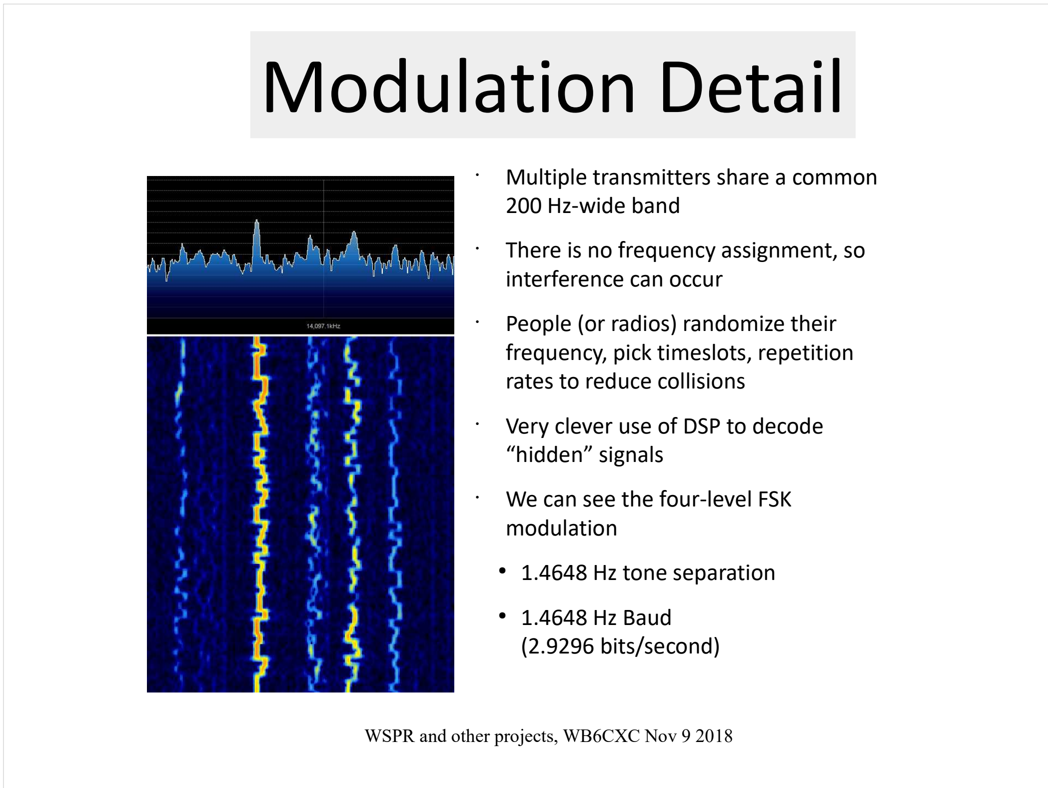
Some of this might be useful in other projects, not just drift-buoys.

Weak Signal Propagation Reporter

- Worldwide: **1000** reporting stations, **1500** transmitting stations
- Operating on USB dial (MHz): 0.136, 0.4742, 1.8366, **3.5686**, 5.2872, 7.0386, 10.1387, 14.0956, 18.1046, 21.0946, 24.9246, 28.1246, 50.293, 70.091, 144.489, 432.300, 1296.500
- Message: Callsign, 4-digit locator, power level in dBm: 50 bits
  - After Forward Error Correction = 162 bits
  - Plus a 162-bit synch pattern = 324 bits
- Modulation
  - 4-FSK (2 bits / symbol)
  - 1.4648 Hz tone separation, 1.4648 Baud
- Duration of transmission: 110.6 seconds
- Transmissions start on even UTC minutes

The number of transmitters and reporting receivers continues to grow.

Note that the 80 meter WSPR frequency has changed to comply with international band usage requlations

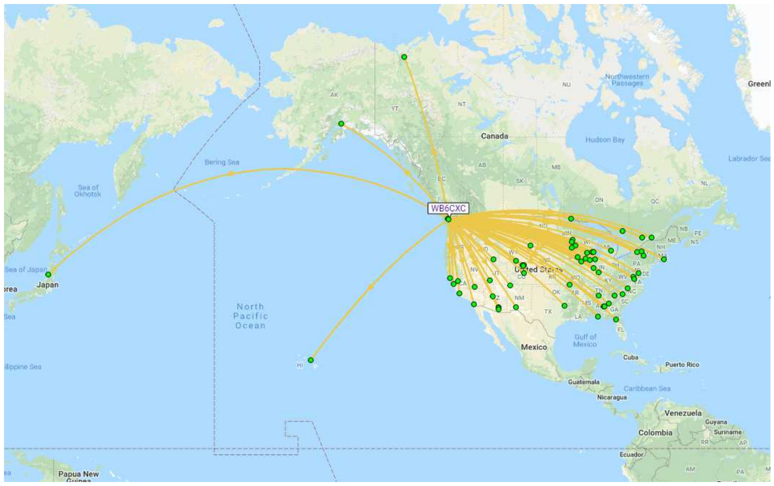


The modulation is designed for low-speed data, and the transmission start-times are tightly synchronized, allowing for optimized receive decoding.

WSPR decoding can make multiple passes over the received spectrum, subtracting previously decoded data to uncover weaker transmissions that would otherwise be masked.

Forward Error Correction is used to enable error-free message decoding in the presence of some individual bit errors.

20-Meter WSPR



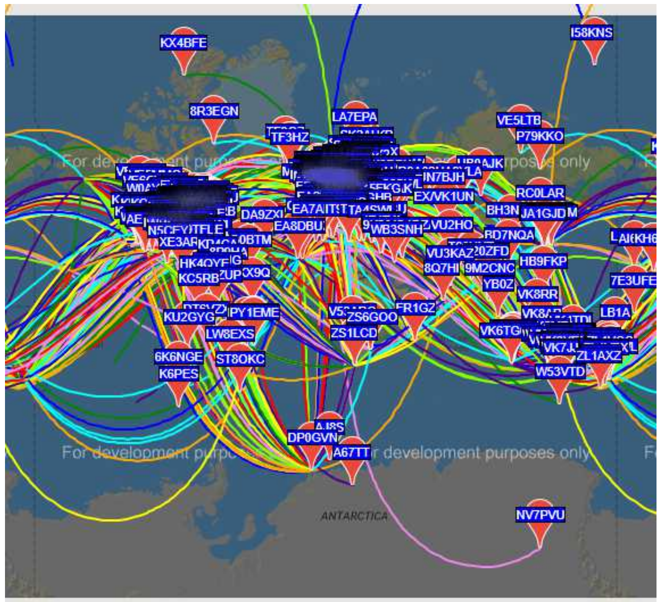
- 5055 miles with 10mW – Friday Harbor to French Guiana
- 690 Miles with 0.1mW – Friday Harbor to Santa Rosa

WSPR and other projects, WB6CXC Nov 9 2018

The map shows places where my 10mW WSPR signal was received during October 2018, during what were considered lousy propagation conditions.

Other paths include 5055 miles to French Guiana with 10mW, and 690 miles to Santa Rosa, CA, transmitting at 100uW

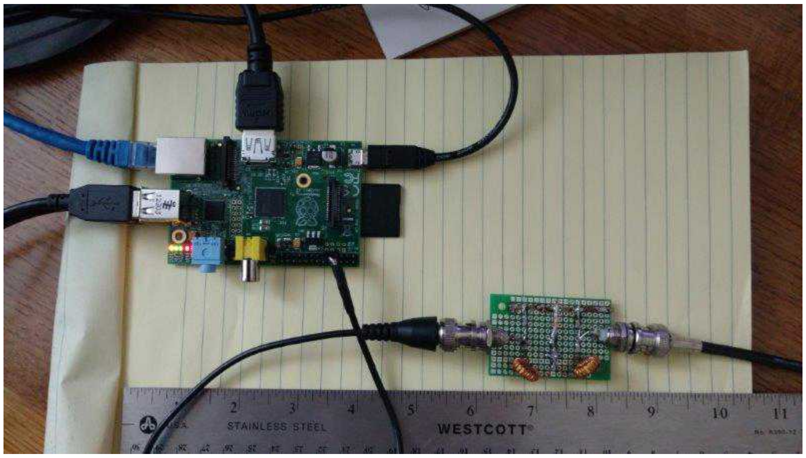
20-Meter WSPR, 24 Hours



WSPR and other projects, WB6CXC Nov 9 2018

You say 20 meters is dead? November 6 worldwide low-power propagation during 24 hours

Raspberry Pi Transmitter, still running 24/7 since December 2015



WSPR and other projects, WB6CXC Nov 9 2018

Running the raw digital output through a 14MHz bandpass filter to get a legal signal.

Other WSPR transmitter designs

- QRP Labs “Ultimate 3S” kit -- $33

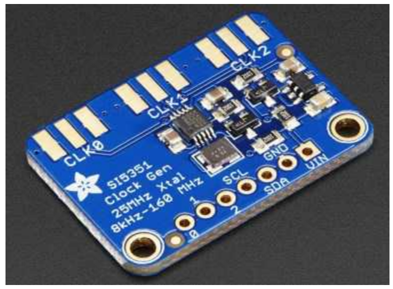
- ZachTek “WSPR-TX_LP1” -- $76

WSPR and other projects, WB6CXC Nov 9 2018

You can also drive a regular SSB transceiver using your computer soundcard interface for transmit modulation and for decoding the received audio.

WSPR Transmitter Designs

- SI5351 Clock Generator, 8 Khz – 160 MHz, $8 from Adafruit



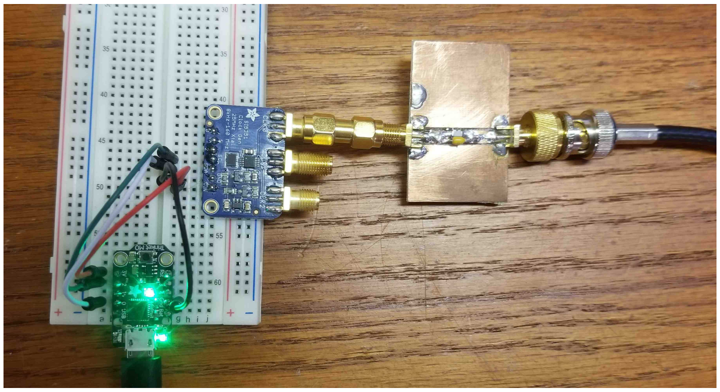
This clock generator chip (or other similar ones) can generate the signals needed for WSPR and other low data-rate FSK modes. The frequency resolution is small fractions of a Hz.

The on-board crystal oscillator isn't stable enough for WSPR at 10 MHz. Measurements using a heat-gun in a cold garage showed a 0.4 ppm / degree C stability, which means a 233 Hz shift at 10 MHz between 0 and 50 deg C. The WSPR band is only 200 Hz wide.

A simple software frequency adjustment could be done using a temperature sensor and a few calibration points. More complicated GPS-calibration could also be done with more circuitry.

Clock Generator Testing

- SI5351 Clock Generator and an Adafruit “Trinket MO” Arduino, running Python.
  - Cheap and easy(Trinket is $8.95) Not a lot of memory.

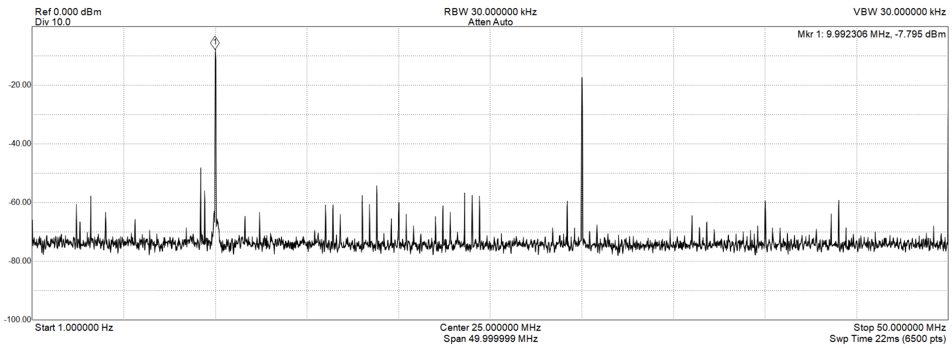


WSPR and other projects, WB6CXC Nov 9 2018

.

SI5351 Clock Generator

- A pretty nice output, will clean up nicely with simple filter



Using on-board 25 MHz xtal

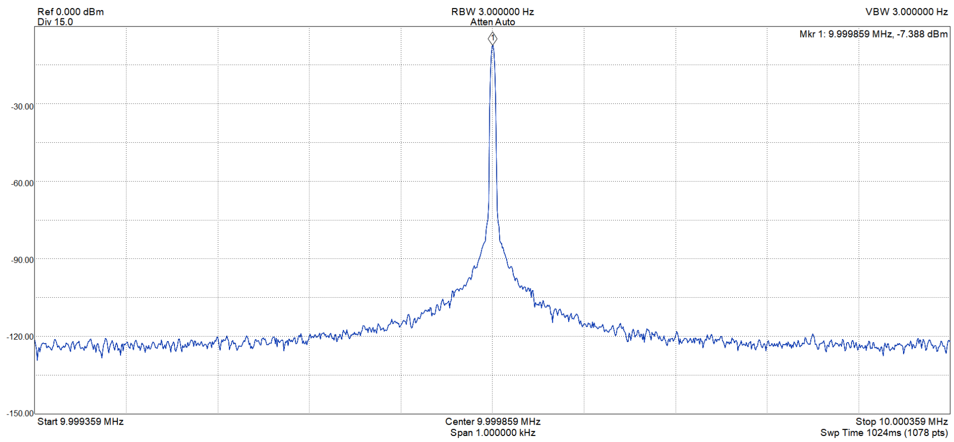
Both the PLL feedback divider and output divider can be integer or fractional

This plot shows output with:
- PLL divider of 20 (500 MHz internal clock)
- Output divider of 50 (gives 10 MHz output)

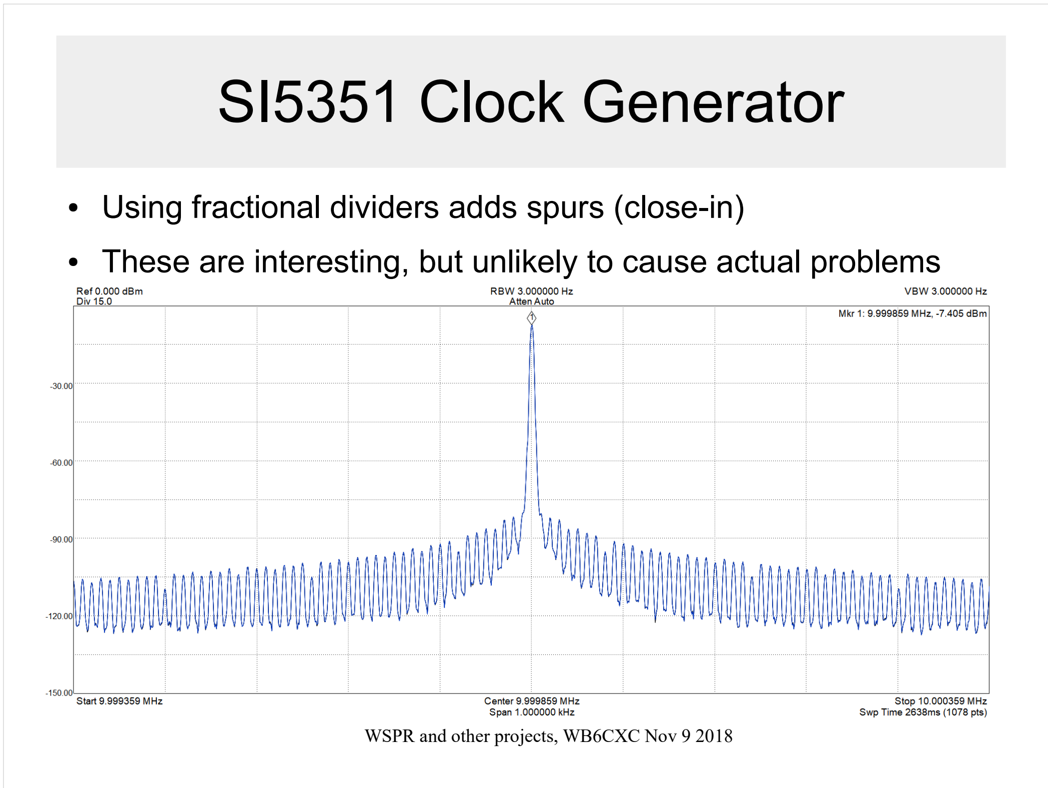
Actual frequency is about 134 Hz low, due to xtal tolerance

SI5351 Clock Generator

- Using integer dividers gives clean output (close-in)



- PLL divider of 20 (500 MHz internal clock)
- Output divider of 50 (gives 10 MHz output)



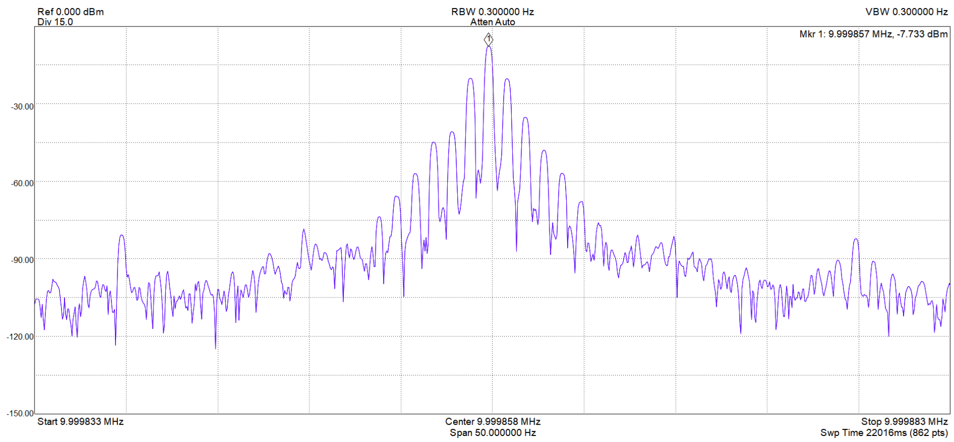
Using fractional output (clock-dropping) divider

This plot shows output with:

- PLL divider of 20 (500 MHz internal clock)
- Output divider of 49 + 1,000,000/1,000,001
- 10,000,000.09999990 MHz output
- Stretches the output by 2ns every 0.1 second (?)

SI5351 Clock Generator

- Using fractional dividers adds spurs (very close-in: 5Hz/div)



WSPR and other projects, WB6CXC Nov 9 2018

Using fractional output (clock-dropping) divider

Stretches the output by 2ns every 0.1 second (?)

There should be 10Hz sidebands, and we do see these. But what causes the closer-in ones???

None of these spurs are present when using the integer dividers.

I need to look at the fractional PLL divider characteristics, but I suspect that any internal PLL loop filtering will not remove these low-frequency spurs. “Faster” ratios should help. Also, there's a “spread spectrum” mode on this chip, but it may be too crude to help here. Careful selection of PLL and output fractional dividers may beneficially spread the spurs.

Balloons and Drift Buoys

- Balloon transmitters circle the planet
  - http://qrp-labs.com/ultimate3/ve3kcl-balloons.html
- Some drift buoys too
  - https://www.qsl.net/zl1rs/oceanfloater1.html
- Ocean Voyager project
  - http://www.jrfarc.org/hf-voyager

Ham Telemetry

- APRS
  - Ability to encode significant amount of data
  - Cloud database access
  - 300 baud FSK, AX.25
  - Non-robust coding, no FEC (FX.25 may add FEC?)
  - Pretty good VHF coverage
    - but not useful for the middle of the ocean
  - Very few HF receiving sites
    - 10 MHz, some using PSK31, 31 bits/second, no FEC

Ham Telemetry

- WSPR
  - Worldwide receiving network and centralized WSPRnet database
  - Some data fields re-purposed for telemetry. A bit of a kludge but used for balloons and supported by WSPRnet. *Very* limited data capacity.
- FT8, JT9
- JS8CALL (AKA FT8CALL)
  - allows free-form text messages
- Satellite: Iridium, Ham

WSPR Telemetry

- Basic WSPR packet: [**Callsign**, **Grid**, **Power** in dBm]
  - Example: WB6CXC CN88LN 10
- Balloons re-use **Power** field for coarse altitude in standard packet
- Second packet uses invalid callsigns, same grid
  - “telemetry flag” and 20 transmitter I.D. values
- Remaining callsign field and other fields give about 23 bits for data
- For more detail, see http://hojoham.blogspot.com/2016/03/wisp1-telemetry.html

Actually, it's more than 23 bits. It's 24 bits minus some values. Still, not a lot of data.

We could invent some other format, but with WSPR we get a worldwide receiving and reporting network. With a custom format we need to have our own receivers.

Also, WSPR is generally accepted. A new system would eat into valuable contesting frequency space. And invite questions about

A Drift-Buoy Project

- Solar-powered buoy, set free to drift with the currents.
- Small, cheap, fun
- Call home with data:
  - Position
  - Temperature
  - Wave data (using 6-axis accelerometer / gyro)
  - Windspeed, direction (using wind/antenna tilt and fluxgate)
  - Status (battery, solar)

Drift-Buoy Challenges

- Power consumption
  - Arduino, GPS, Sensors
  - Efficient transmitter
  - Solar panel
- Communications modes
- Short antenna
- Flotation
- Waterproof
- Programming

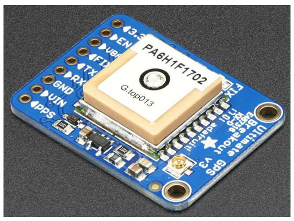
Power consumption is critical. Large solar panels are vulnerable, and there are many cloudy days. We need to keep power usage to a minimum by turning off sub-systems whenever we can, and by using power-efficient circuitry.

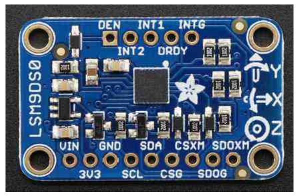
Arduino-style controllers, rather than Raspberry Pi, and minimizing transmitter power and time will help. Battery needs to be big enough to work through the night, and panels need to be big enough to recharge battery fully during a cloudy winter day.

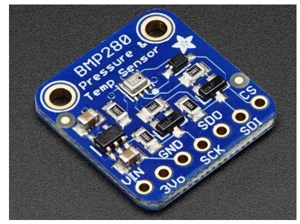
Will have a “power-saver” mode to reduce operations when battery is getting low.

Sensors

- Adafruit “Ultimate GPS Breakout” - $39.95
- Adafruit 9-DOF Accel / Gyro / Magnetometer - $14.95
- Adafruit Barometric Pressure + Temperature - $9.95
- Similar items available from Sparkfun, China







There are many inexpensive sensors out there. Adafruit and Sparkfun are excellent sources.

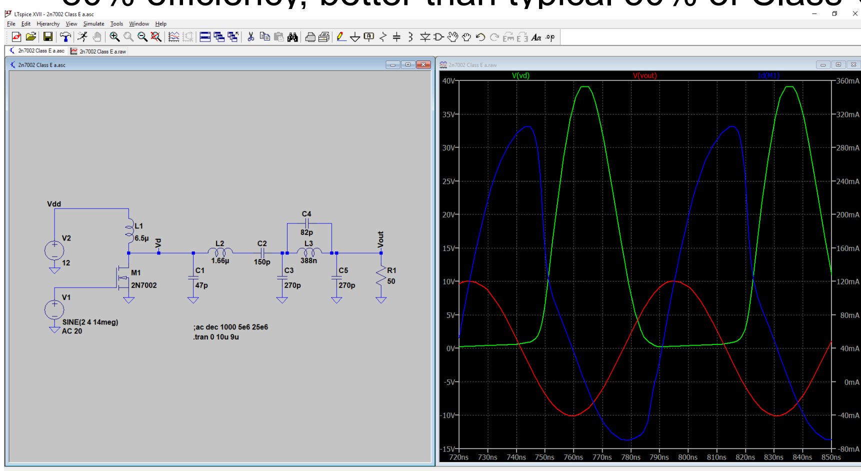
Getting the environmental data is the easy part, but transmitting it through extremely limited telemetry channels will be tough. We will probably only be able to send a fraction of what we would like to do.

Short Vertical Antenna

- 102” whip is 0.086 wavelength at 10 MHz
- Very low radiation resistance, small series capacitance
- **2.9 Ohms radiation resistance**
- 16pF series capacitance, needs 16uH loading coil
  - (or 25pF / 10uH – depending on which equations)
- Good news: excellent seawater ground
- Bad news: very high Q loading coil required
  - Q of 50 adds 13dB additional loss (ideal ground)
  - Q becomes less critical with larger ground losses

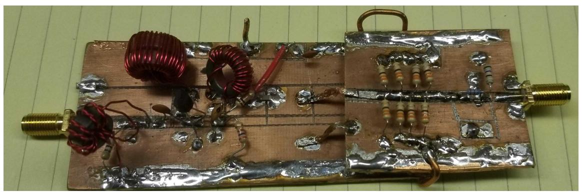
Drift-Buoy Transmitter

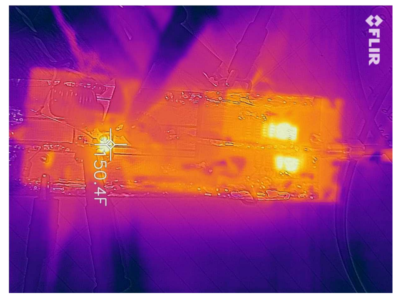
- Class-E output stage, 1W, 10 MHz
  - 80% efficiency, better than typical 50% of Class-C



Drift-Buoy Transmitter

- Breadboard Class-E output stage, 1.5W, 10 MHz
  - Thermal image confirms TO-92 transistor dissipating about 150mW (thermal resistance calculation)
  - Dummy load resistors burning around 1.5W





Test Equipment

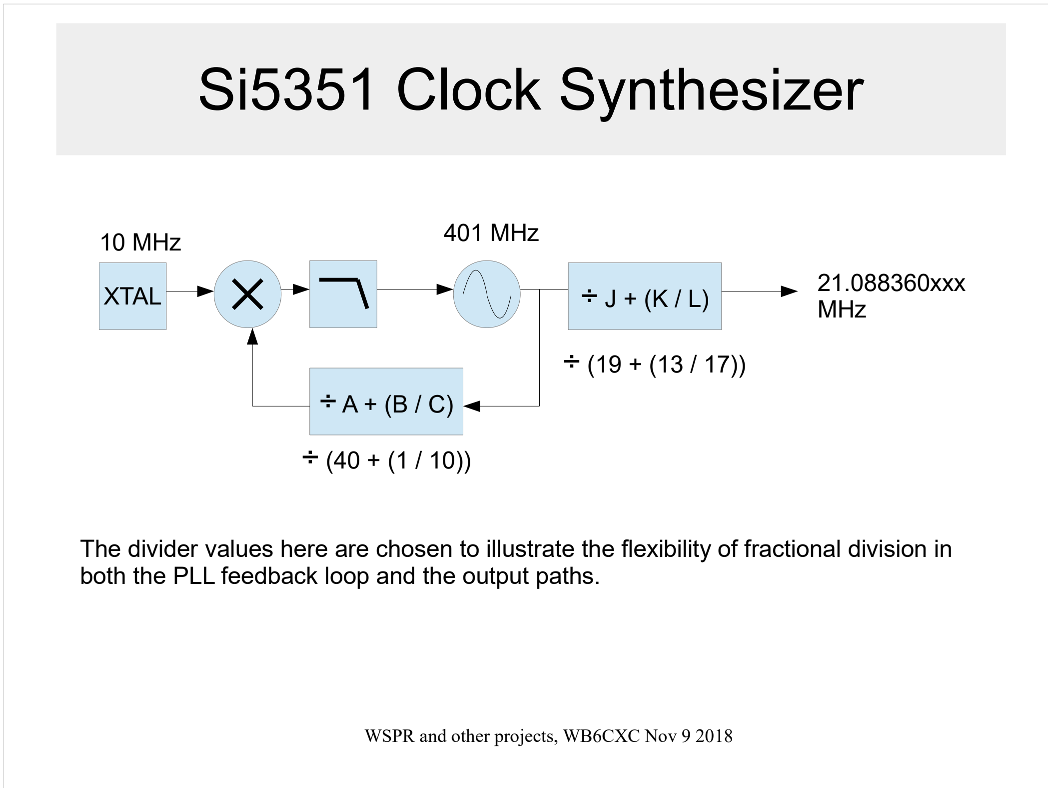
Test Equipment

- Power supply, DVM
- Oscilloscope
- Signal generator
- Spectrum analyzer, tracking generator, directional coupler
- Antenna analyzer (Bluetooth)
- Dummy loads, attenuators, cables, adaptors (N, BNC, SMA)
- Receivers (ham, SDR)
- Precision 10MHz reference (OCXO, Rubidium, GPS-disciplined)

Breadboarding

- Woodcarving “V-Tool” gouge used to carve copper lands on PCB
- Clamps and steel rule for straighter lines and less blood-loss
- Copper foil for low-Z paths

- Chinese SMA connectors are $1 ea.



This is the structure of one of the PLL clock synthesizers inside the Si5351 chip.

What makes it special is the fractional dividers in the PLL feedback loop, and at the output. A fractional divider will divide an input clock by an integer, but will also skip clocks at a ratio set by the numerator and denominator of the fraction. A typical fractional divider will spread out these skipped clocks as evenly as possible in order to reduce jitter.

In some cases, the skipped clock spacing is deliberately randomized (AKA Spread Spectrum or Noise Modulation) to reduce coherent spectral spurs.

Links

- Previous WSPR Presentation: http://wb6cxc.com/?page_id=65
- WSJT-X: https://physics.princeton.edu/pulsar/k1jt/wsjtx.html
- WSPRnet: http://wsprnet.org
- WSPR Telemetry: http://hojoham.blogspot.com/2016/03/wisp1-telemetry.html
- WSPR on Pi: https://github.com/JamesP6000/WsprryPi
- Balloons: http://qrp-labs.com/ultimate3/ve3kcl-balloons.html
- Drift buoys: https://www.qsl.net/zl1rs/oceanfloater1.html
- QRP Labs: https://www.qrp-labs.com/ultimate3
- Moetronix WSPR beacon: http://moetronix.com/wspr.html
- ZachTech: https://www.zachtek.com

Links

- Adafruit: https://www.adafruit.com/product/2045
- Sparkfun: https://www.sparkfun.com/products/13339
- Class E Amplifier:
  - http://people.physics.anu.edu.au/~dxt103/160m/class_E_amplifier_design.pdf
  - http://www.norcalqrp.org/files/Class_E_Amplifiers.pdf
- Short vertical antenna:
  - https://www.qsl.net/l/lu7did/docs/QRPp/09.pdf
  - http://people.physics.anu.edu.au/~dxt103/calculators/Rrad.php
  - http://www.strobbe.eu/on7yd/136ant/#ShortMonopole