RADIO MAGiC

Robert C. Mazur, VA3ROM | www.va3rom.com | va3rom@gmail.com

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Telemetry-over-WSPR: Part 1

Introduction

Special thanks to Dave Beverstein, VE3KCL, for providing additional information about the Amateur Radio telemetry-over-WSPR ballooning world.

The weak signal propagation reporter (WSPR) or “whisper” digital data mode was originally only used for one-way propagation beacons. Created in 2008 by Joe Taylor, K1JT, the standard WSPR type 1 (of 3) bundle of bits or packets consists of 162 mathematically encoded combinations of the numbers 0, 1, 2 and 3 (called symbols) representing a transmitting station’s callsign, 4-character Maidenhead grid square locator and transmitter power in decibel-milliwatts (dBm). WSPR is transmitted within designated digital sub-bands only 200 Hz wide by either 4-frequency shift keying (4-FSK) or 4-tone audio FSK (4-AFSK) using 1.465 hertz (Hz) frequency/tonal shifts multiplied by the appropriate symbol. Transmissions must start within the first few seconds of any even minute and beacons take just under 111 seconds so it’s a very slow data and narrow bandwidth data mode (about 6 Hz and 6 baud). But because of this, WSPR’s power spectral density (PSD) measured in watts per Hz (W/Hz) is also 400 times greater than a sideband signal (2500 Hz reference bandwidth)! So it packs a powerful punch and can now be decoded with signal-to-noise ratios (SNR) as bad/low as minus 32 dB (hence the weak signal moniker). This is because of ongoing mathematical improvements to the algorithms used by the digital signal processing (DSP) software called “WSJT-X” used to generate WSPR and other weak signal modes.

There's a world-wide collective of transmitting/receiving stations that form the "WSPRnet" wherein Amateurs can do both while other radio hobbyists are receive only but both can stream or "spot" signals on frequencies ranging from 136 kilohertz (kHz) to 1296 gigahertz (GHz) to the WSPRnet server 24/7/365. The WSPRnet currently contains terabytes of invaluable "nuggets" (going back to March 2008) being data mined by individuals, students, groups and researchers for various transmitter and antenna tests, ionospheric and solar research related projects, etc.

It All Started with a Small Balloon

Amateurs who regularly fly party foil (pico) helium filled balloons or other larger types of Amateur Radio high altitude balloons (ARHAB)—most notably Dave Beverstein, VE3KCL—have pioneered the use of telemetry-over-WSPR QRPp (very low power) transmitters with Hans Summers, G0UPL's (QRP Labs) amazing U4B multiple digital data modes transmitter (Figure 1). Telemetry data are downloaded from the WSPRnet and decoded using a custom spreadsheet (Excel).

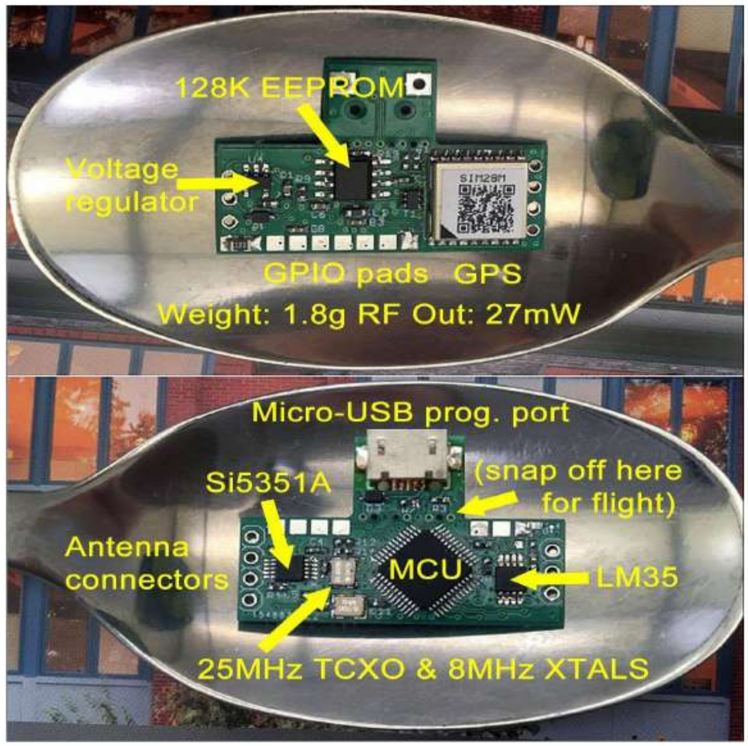


Figure 1: U4B Balloon Tracker Module
Image credit: QRP Labs

There's no official "rulebook" as to the encoding method you must use or what sensor telemetry each WSPR field or character in each field must represent, but there're conventions that have been developed and adopted by the Amateur Radio ballooning community: transmitter "channelization" and broadcast "slots" within each WSPR sub-band, using the first and third characters of telemetry callsigns to create unique balloon flight identifiers plus posting their flight information on the QRP Labs balloon flight information and tracking webpage. The 20 metre WSPR band segment (FSK carrier 14097.100 kHz +/- 100 Hz) is widely used by Amateur Radio ballooners.

The all-in-wonder U4B has several built-in sensors and transmits a balloon's GPS position, altitude, ground speed while other sensors transmit battery voltage and ambient air temperature using QRP Labs' telemetry-over-WSPR encoding protocol. A few additional user supplied components are required to complete the flight package: solar panel, rechargeable battery pack, trailing wire antenna(s) and any additional sensors—subject to the maximum lifting capacity of the helium gas filled balloon used. *Note: COVID-19 has severely affected the global availability of many badly needed and now very scarce electronic chips and components across all industries and the U4B is currently out of stock.*

Position	Possible Values	Number of Possible Values
Callsign 1	Q,0	2
Callsign 2	0-9, A-Z	36
Callsign 3	0-9	10
Callsign 4	A-Z	26
Callsign 5	A-Z	26
Callsign 6	A-Z, space	27
Gridsquare 1	A-R	18
Gridsquare 2	A-R	18
Gridsquare 3	0-9	10
Gridsquare 4	0-9	10
DBM	0-18	19

Table 1: WSPR Telemetry Format
Image credit: Michael, "Hojo", KD2EAT

WSPR Telemetry Encoding Methods

I found an easy to understand encoding/decoding methods on Michael Hojnowski, KD2EAT's, "Hojo's Ham Blog" website wherein he reveals some of the behind the scene "magic" (Table 1). Ballooners only use WSPR type 1 transmissions, but there's a nifty trick to encode greater GPS positional accuracy by using two characters of the telemetry callsign to hold the 5 and 6 characters of the enhanced 6-character grid square, simulating a WSPR type 2 transmission.

There's also a link to Dave, VE3KCL's, variation (https://tinyurl.com/mtjsymef). The most important take-away is that any callsigns starting with the alphanumeric characters "0" (zero), "1" (one) or "Q" are not assigned in the Amateur Radio Service and are being used to denote telemetry-over-WSPR transmissions, which makes it much easier to search the for telemetry beacons.

Note: There's some unofficial use of the unassigned "1" prefixes: 1A by the Sovereign Military Order of Malta, 1B by the Turkish Republic of Northern Cyprus (only recognized by Turkey) plus 1C and 1X sometimes used by separatists in Chechnya (a republic of Russia).

First Telemetry Beacon Project

Last year, I wrote about my 22 metre (m) industrial, scientific and medical (ISM) band QRPp, very slow (QRSS) speed FSK Morse code telemetry beacon experiments (*TCA* Jan-Feb and Mar-Apr 2021). FSK Morse did the job but required up to eight minutes to transmit an encoded telemetry packet containing the environmental conditions at my remote trailer park camp site. It also required "fuzzy" logic visual decoding of the telemetry (by me) because this QRSS mode "paints" scrolling images (or "grabs") on your computer monitor and saving them to the hard drive every 10 minutes (after enhancement using image stacking). The advantage is that you'll still see something even if the signal is intermittent and can then fuzzy logic fill-in the missing data because we humans are very good at pattern recognition especially if we know what came before and what followed after.

On the other hand, WSPR is an "all-or-nothing" mode and partial decodes aren't possible. If WSJT-X (or other decoding software) can't repair whatever is wrong with the packet then everything is rejected at the receiving end as if the packet never existed! The 22 m band "sweet spot" sub-band (FSK carrier 13555.400 kHz +/- 100 Hz) is now officially recognized for international WSPR use, much to the consternation of long-time QRSS FSK users and other non-Amateur radio hobbyists. The maximum power allowed is only 4.7 milliwatts (mW) to a standard dipole (no gain antennas) but many Amateurs don't realize that 22 m is an ISM band and the operating rules are different for ISM bands.

WSPR Propagation and Telemetry Gadget

After looking over two popular telemetry-over-WSPR encoding/decoding methods, I rejected both and simplified things by only using predefined values stored in a lookup table and only encoded/decode sensor telemetry using the callsign field (numbers 0 to 9 and characters A to Z). I also moved to the 40 m WSPR sub-band, upped the power to 20 dBm (100 mW) and used a low-to-the-ground sloping dipole with a 15 m run of RG58 coaxial feed line. This maximized the data collection in a faster time because there's more on-air monitoring stations, but I was also interested in the near and long range performance of the transmitter/antenna system and needed a lot of data to do so. Surprisingly, there seems to be a combination of both over the course of the day (Figures 2A and 2B, next page).

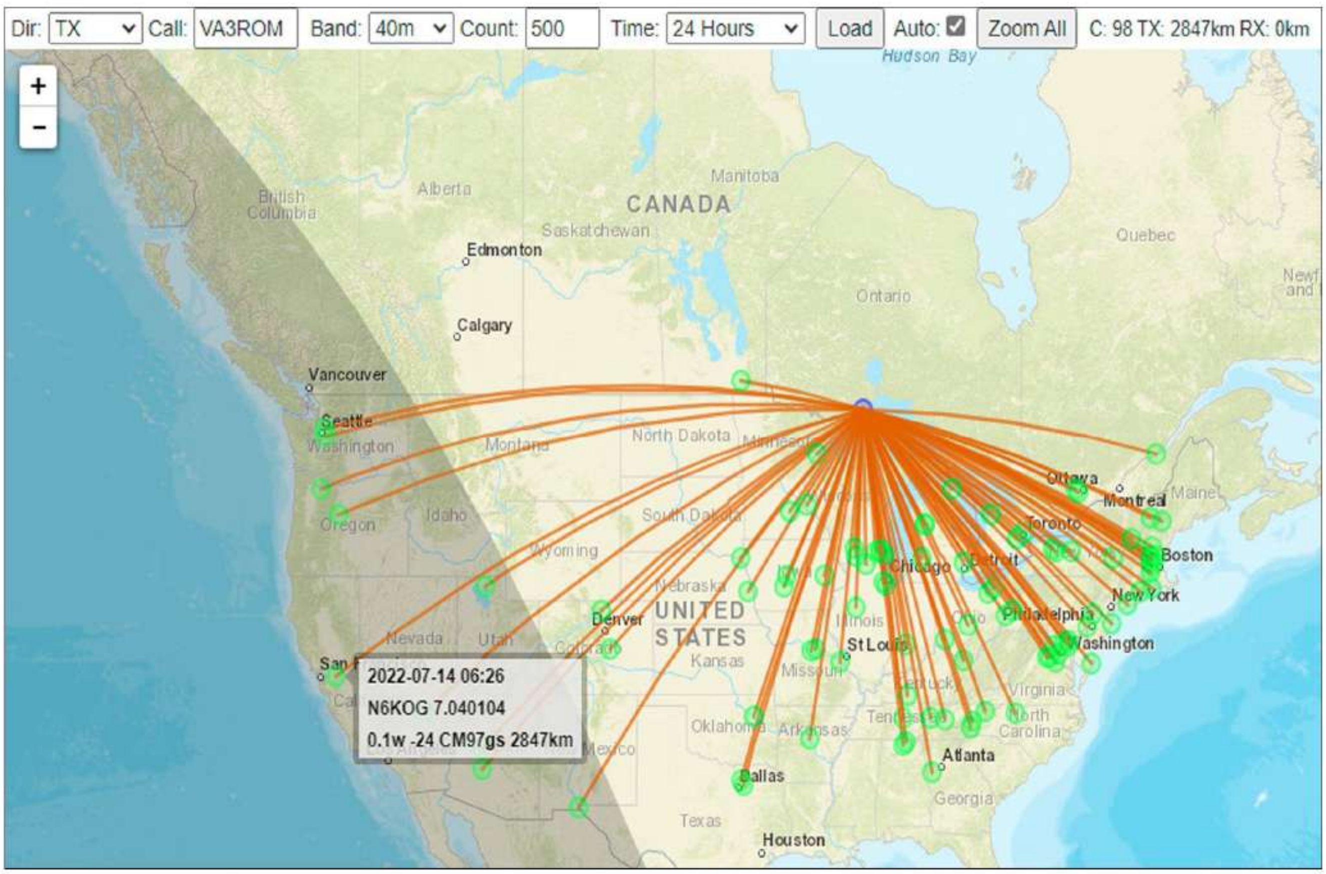


Figure 2A: WSPR Propagation/Telemetry Beacon 24-Hour Reception

Even low to the ground dipole can throw QRPp WSPR signals near (day) and far (night). Image credit: http://wspr.aprsinfo.com

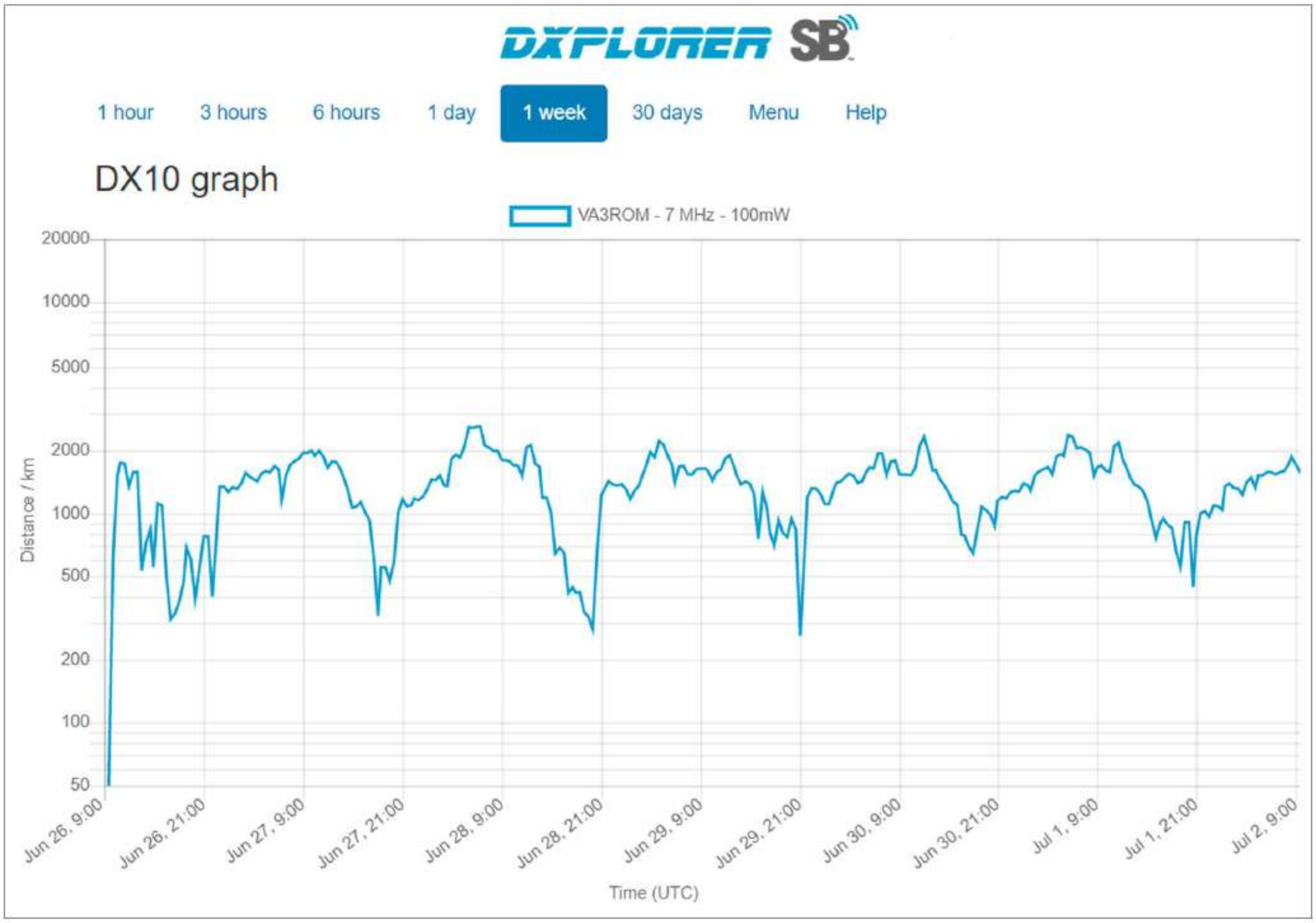
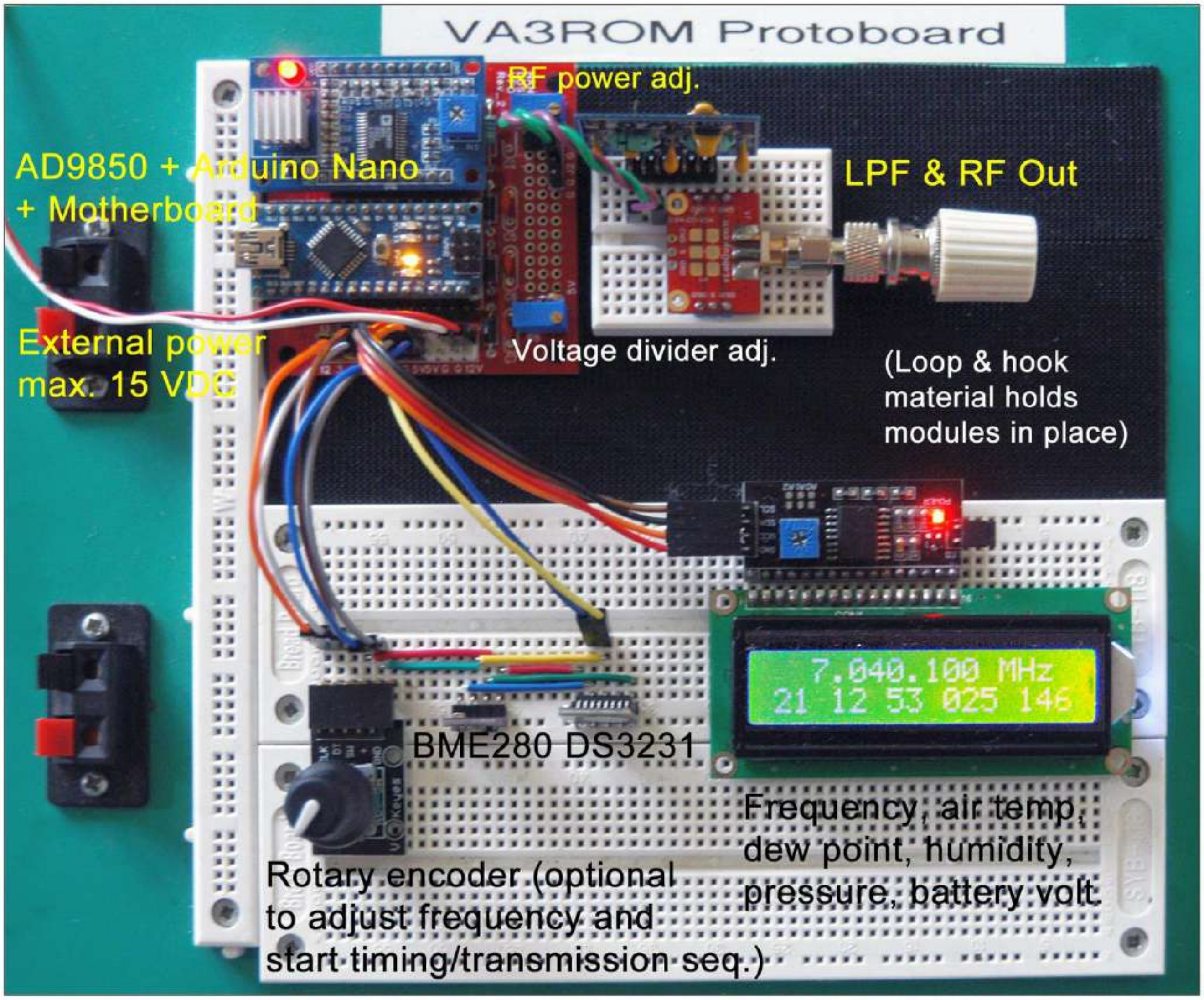


Figure 2B: WSPR Propagation/Telemetry Beacon Multiday Reception
Note the repeating diurnal propagation patterns. Image credit: http://dxplorer.net

Because the U4B wasn't available, my prototyping solderless breadboard was used to build my experimental telemetry-over-WSPR transmitter composed of an Arduino Nano microcontroller plus the AD9850 direct digital synthesiser (DDS) mounted on a motherboard kit bought and built for another transceiver project (Figure 3, next page). The DDS motherboard is no longer available but QRP Labs sells their "Ultimate" Arduino Uno shield transmitter kit that supports the AD9850/AD9851 or Si5351A DDS (more in part 2). The DDS motherboard has a built-in analog 3:1 resistive voltage divider connected to the 12 volt battery/solar power system being monitored, along with an added BME280 sensor to monitor the ambient air temperature, relative humidity and air pressure plus a mini-DS3231 real-time-clock (RTC) module instead of using a GPS because my transmitter doesn't float around the Earth. The RTC has a temperature compensated crystal oscillator (TCXO) and keeps very good time even with changes in ambient air temperatures.

Figure 3: My WSPR Propagation/Telemetry Transmitter Arduino Nano Gadget



Data from the sensors are encoded using Table 2 (next page) and transmitted every 10 minutes (QRSS standard transmission frame or window). Because dew point temperature is derived from air temperature and relative humidity by using a simple equation it doesn't need to be transmitted so I could add another (second) sensor. While only the callsign characters are used to encode telemetry, the dBm field is still available to encode another 19 different values (third sensor) however, the grid square locator field is always used for its positional purpose but it can also be used, if needed.

Table 2: Encoding/Decoding of Sensor Telemetry

This table depicts the method used to encode/decode my sensor data.

Telemetry Encoding/Decoding Lookup Tables

TP & DP		RH	%	P	mB	VDC	Volts
A	-10	0	0	A	975	A	10.0
B	-8	1	10	B	978	B	10.2
C	-6	2	20	C	981	C	10.4
D	-4	3	30	D	984	D	10.6
E	-2	4	40	E	987	E	10.8
F	0	5	50	F	990	F	11.0
G	2	6	60	G	993	G	11.2
H	4	7	70	H	996	H	11.4
I	6	8	80	I	999	I	11.6
J	8	9	90	J	1002	J	11.8
K	10			K	1005	K	12.0
L	12			L	1008	L	12.2
M	14			M	1011	M	12.4
N	16			N	1014	N	12.6
O	18			O	1017	O	12.8
P	20			P	1020	P	13.0
Q	22			Q	1023	Q	13.2
R	24			R	1026	R	13.4
S	26			S	1029	S	13.6
T	28			T	1032	T	13.8
U	30			U	1035	U	14.0
V	32			V	1038	V	14.2
W	34			W	1041	W	14.4
X	36			X	1044	X	14.6
Y	38			Y	1047	Y	14.8
Z	40			Z	1050	Z	15.0

Transmission Sequence

1. The transmission sequence is: on first even minute transmit standard WSPR type 1 propagation beacon: Example: “VA3ROM EN58 20” (this never changes, it’s fixed)

2. Followed immediately on the next even minute by a telemetry-over-WSPR telemetry beacon: Example: “0G6GJF EN58 20” (the 2nd to 6th callsign characters change)

3. Followed by six minutes of idling (transmitter off) to conserve battery/solar power and also clear the frequency for other WSPR transmissions.

The Encoding Magic

On-the-fly generation of the constantly changing 162-bit WSPR packet is mathematically "intense", fortunately Jason Milldrum, NT7S, has created an awesome Arduino support library called "JTEncode". This library not only handles WSPR but also the JT65, JT9, JT4, FT8 and FSQ digital data modes plus it also supports direct control of the Si5351A DDS, which has become the de facto DDS of choice by Amateurs and other radio hobbyists. There's no built-in AD9850/AD9851 support but there're several Arduino libraries available.

The Arduino program counts the second ticks supplied by the RTC module to determine the next transmission time and controls the DDS during the FSK transmission of a WSPR type 1 propagation beacon. Then it reads the voltage divider and BME280, encodes their data using Table 2, and transmits the WSPR type 1 telemetry on the next even minute. *Note: So long as the telemetry-over-WSPR encoding/decoding methodology is made public and not designed to obscure its meaning it's not considered as "encryption", which is a no-no to use on any Amateur Radio band. However, the 22 m band is a different because it's designated as an experimental, unlicensed, QRPp ISM band that's open to any and all radio hobbyists as secondary users (must not interfere with primary users). Many commercial devices on 22 m use encryption such use tap-and-pay card readers, biometric passports, medical equipment and monitoring equipment, etc. The 22 m frequency around 13560 kHz is "alive" with the sounds of encrypted tap-and-pay card readers.*

Example of encoding telemetry callsign "0M6JJF" (using Table 2):

Callsign position 1: telemetry beacon callsign (first character indicator "0")
Callsign position 2: encoded temperature range (in 2 degree Celsius intervals)
Callsign position 3: encoded relative humidity range (in 10% intervals)
Callsign position 4: encoded dew point range (in 2 degree Celsius intervals)
Callsign position 5: encoded air pressure range (in 3 millibar intervals)
Callsign position 6: encoded battery/solar voltage range (in 0.5 volt intervals)

The Decoding Magic

Example of decoding telemetry callsign "0G6GJF" (using Table 2):

1. Telemetry-over-WSPR beacon (first character is "0")
2. Air temperature between 14 and 16 degrees Celsius
3. Relative humidity between 60 and 70 percent
4. Dew point temperature between 8 and 10 degrees Celsius
5. Air pressure between 1002 and 1005 millibars or 100.2 and 100.5 kilopascals. *Note: The millibar is also the SI (metric unit) hectopascal.*
6. Battery/solar voltage between 11.0 and 11.2 volts

Sample Spreadsheet Telemetry Analysis

A moving smoothed average with a period of six (one hour's worth of telemetry transmissions) smoothes line data plots (red). Graphing telemetry is a great way to build a picture as a function of time as more and more data is collected to see what's really happening, and what you may need to do to correct any problems. For example, many Amateur's use radios with uncorrected dial frequency errors that read either too high or too low, various sensors also have +/- errors and most microcontroller's crystal oscillator "heartbeats" are never ever spot on frequency and introduce more +/- (timing) errors. After a while, these collective errors all add together, which really skews the data and can give you a totally wrong impression of the world around you that you're monitoring! And your own confirmation bias can compound the errors!

You can determine and compensate for most constant/repeating errors in the encoding program code and/or decoding spreadsheet except in the case where the error may have a known cause but its effects are random and it's difficult to come up with an equation to correct for it. Because there's no TCXO version of the AD9850 its output frequency wanders up and down and it's very difficult to figure out an equation to correct for this (Figure 4, next page). I know that some negative coefficient is involved but that's all that I can determine. Inside a climate controlled environment it's fairly frequency stable, but in an unheated, uninsulated habitat it's becomes very problematic because your WSPR signal will wander around and can interfere with others and/or can possibly move in/out of the WSPR sub-band!

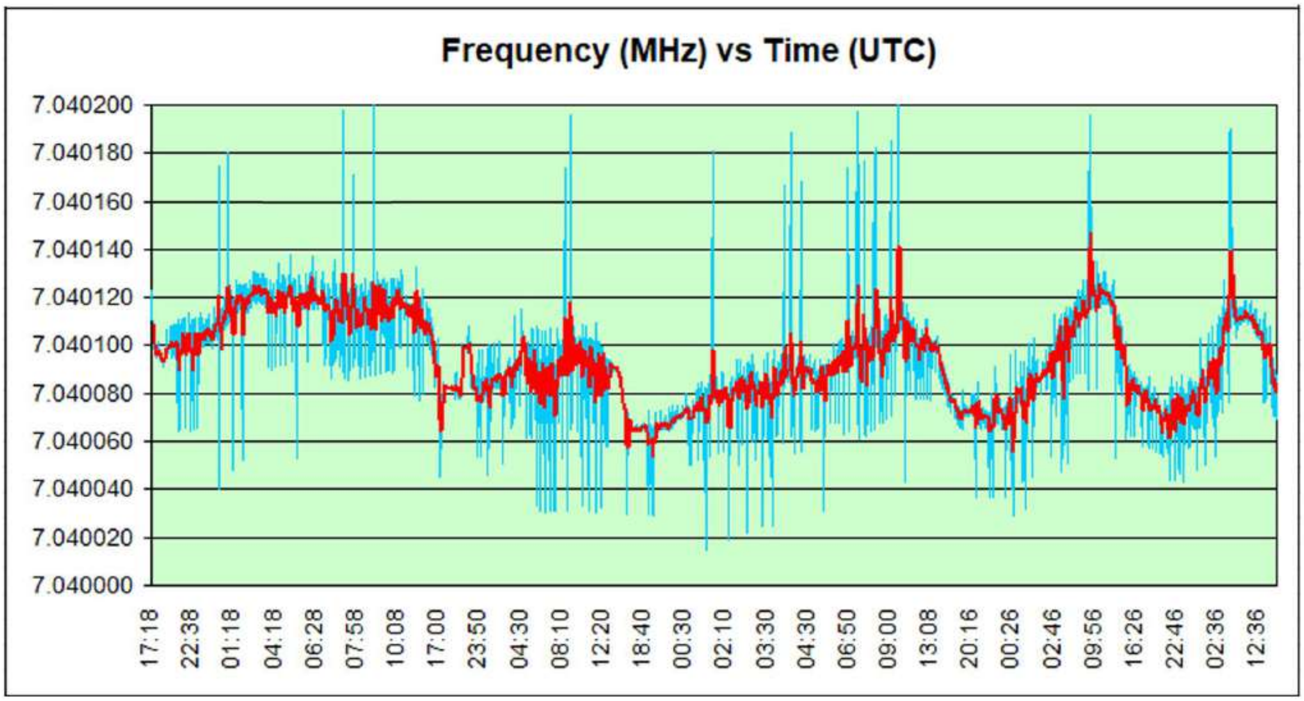


Figure 4: AD9850 DDS Frequency Variance with Temperature

The lack of a TCXO shows how much this AD9580's DDS output frequency is affected by ambient air temperature changes.

WSPR telemetry transmissions spotted by others to the WSPRnet are manually collected by myself every few hours using a "0*" wildcard callsign search then imported into a custom Excel decoding spreadsheet. As shown in the sample spreadsheet (Figure 5, next page), the mean value DDS transmitter frequency is 6 Hz low while the mode is 17 Hz high. The actual FSK carrier frequency should be 7040.100 kHz. The variance from the mean frequency indicates that there's a problem but we already know what the cause is, in this case. The battery voltage levels and solar panel charging cycles (voltage peaks) are tracking nicely with diurnal (day/night) and cloudy caused variations (Figure 6, next page). Everything seems to be okay so anything requiring battery/solar power should be operating properly.

Microsoft Excel - (40 m Jun 2022) WSPR Telemetry Beacon Decoding Sheet

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	**WSPR Telemetry Decoding Sheet AD9850 DDS**																							
2															Var +/- Hz	50.0								
3															Mode	7.040117								
4		Min		10.0		20.0		4.0		1002.0		11.8			Min	7.040015	-32.0	-4.0				Min	491.0	102.0
5		Max		32.0		70.0		22.0		1017.0		12.6			Max	7.040209	1.0	4.0				Max	2925.0	281.0
6		Mean		19.2		45.6		10.2		1008.9		12.1			Mean	7.040094	-19.4	-0.2				Mean	912.3	155.0
7	UTC Date	Time		TP C		RH %		DP C		P mB		VDC		Timestamp	Call	MHz	SNR	Drift	Grid	Pwr	Reporter	RGrid	km	az
8	2022-06-19	17:18	L	12	7	70	J	8	O	1017	K	12.0		2022-06-19 17:18	0L7JOK	7.040123	-15	-4	EN58	0.1	KX4AZ/T	EN74gc	559	149
9	2022-06-19	17:28	M	14	6	60	J	8	O	1017	K	12.0		2022-06-19 17:28	0M6JOK	7.040113	-14	-1	EN58	0.1	KX4AZ/T	EN74gc	559	149
10	2022-06-19	17:38	M	14	6	60	J	8	O	1017	K	12.0		2022-06-19 17:38	0M6JOL	7.040110	-19	0	EN58	0.1	KX4AZ/T	EN74gc	559	149
11	2022-06-19	17:48	M	14	6	60	J	8	O	1017	M	12.4		2022-06-19 17:48	0M6JOM	7.040106	-16	0	EN58	0.1	KX4AZ/T	EN74gc	559	149
12	2022-06-19	17:58	N	16	6	60	J	8	O	1017	M	12.4		2022-06-19 17:58	0N6JOM	7.040101	-21	0	EN58	0.1	KX4AZ/T	EN74gc	559	149
13	2022-06-19	18:08	N	16	6	60	K	10	O	1017	N	12.6		2022-06-19 18:08	0N6KON	7.040098	-15	-1	EN58	0.1	KX4AZ/T	EN74gc	559	149
14	2022-06-19	18:18	N	16	6	60	K	10	O	1017	N	12.6		2022-06-19 18:18	0N6KON	7.040096	-6	0	EN58	0.1	KX4AZ/T	EN74gc	559	149
15	2022-06-19	18:28	N	16	6	60	K	10	O	1017	N	12.6		2022-06-19 18:28	0N6KON	7.040096	-14	0	EN58	0.1	KX4AZ/T	EN74gc	559	149
16	2022-06-19	18:38	O	18	6	60	K	10	O	1017	N	12.6		2022-06-19 18:38	0O6KON	7.040096	-19	0	EN58	0.1	KX4AZ/T	EN74gc	559	149
17	2022-06-19	18:48	O	18	6	60	K	10	O	1017	N	12.6		2022-06-19 18:48	0O6KON	7.040095	-17	0	EN58	0.1	KX4AZ/T	EN74gc	559	149
18	2022-06-19	18:58	O	18	5	50	J	8	O	1017	M	12.4		2022-06-19 18:58	0O5JOM	7.040096	-29	0	EN58	0.1	K3FEF	FN21mh	1362	121
19	2022-06-19	18:58	O	18	5	50	J	8	O	1017	M	12.4		2022-06-19 18:58	0O5JOM	7.040097	-16	0	EN58	0.1	KX4AZ/T	EN74gc	559	149
20	2022-06-19	18:58	O	18	5	50	J	8	O	1017	M	12.4		2022-06-19 18:58	0O5JOM	7.040102	-22	0	EN58	0.1	N0NAS	EN34qt	491	215
21	2022-06-19	19:08	O	18	5	50	J	8	O	1017	M	12.4		2022-06-19 19:08	0O5JOM	7.040097	-21	0	EN58	0.1	KX4AZ/T	EN74gc	559	149
22	2022-06-19	19:18	O	18	5	50	J	8	O	1017	M	12.4		2022-06-19 19:18	0O5JOM	7.040097	-27	-1	EN58	0.1	KX4AZ/T	EN74gc	559	149
23	2022-06-19	19:28	O	18	5	50	J	8	N	1014	M	12.4		2022-06-19 19:28	0O5JNM	7.040097	-17	0	EN58	0.1	KX4AZ/T	EN74gc	559	149
24	2022-06-19	19:38	O	18	5	50	J	8	N	1014	M	12.4		2022-06-19 19:38	0O5JNM	7.040097	-16	1	EN58	0.1	KX4AZ/T	EN74gc	559	149
25	2022-06-19	19:38	O	18	5	50	J	8	N	1014	M	12.4		2022-06-19 19:38	0O5JNM	7.040095	-23	0	EN58	0.1	VE3TAZ	EN96	641	107
26	2022-06-19	19:38	O	18	5	50	J	8	N	1014	M	12.4		2022-06-19 19:38	0O5JNM	7.040094	-16	1	EN58	0.1	VE3TYA	EN96cg	598	112
27	2022-06-19	19:48	O	18	5	50	J	8	N	1014	M	12.4		2022-06-19 19:48	0O5JNM	7.040093	-12	0	EN58	0.1	VE3TYA	EN96cg	598	112
28	2022-06-19	19:58	O	18	5	50	K	10	N	1014	N	12.6		2022-06-19 19:58	0O5KNN	7.040095	-17	0	EN58	0.1	KX4AZ/T	EN74gc	559	149
29	2022-06-19	20:08	O	18	5	50	K	10	N	1014	M	12.4		2022-06-19 20:08	0O5KNM	7.040093	-16	0	EN58	0.1	KX4AZ/T	EN74gc	559	149
30	2022-06-19	20:18	O	18	5	50	K	10	N	1014	M	12.4		2022-06-19 20:18	0O5KNM	7.040093	-17	0	EN58	0.1	KX4AZ/T	EN74gc	559	149
31	2022-06-19	20:28	O	18	5	50	K	10	N	1014	M	12.4		2022-06-19 20:28	0O5KNM	7.040094	-5	0	EN58	0.1	KX4AZ/T	EN74gc	559	149
32	2022-06-19	20:28	O	18	5	50	K	10	N	1014	M	12.4		2022-06-19 20:28	0O5KNM	7.040091	-23	-1	EN58	0.1	VE3TAZ	EN96	641	107
33	2022-06-19	20:38	O	18	5	50	K	10	N	1014	L	12.2		2022-06-19 20:38	0O5KNL	7.040097	-16	0	EN58	0.1	KX4AZ/T	EN74gc	559	149

WSPR Beacon

Figure 5: WSPR Spreadsheet WSPR Data Analysis (AD9850 DDS Transmitter)

A lot of information can be gleaned from the WSPRnet. But there're many "nuggets" hidden within the WSPRnet "gold mine" one can sift through.

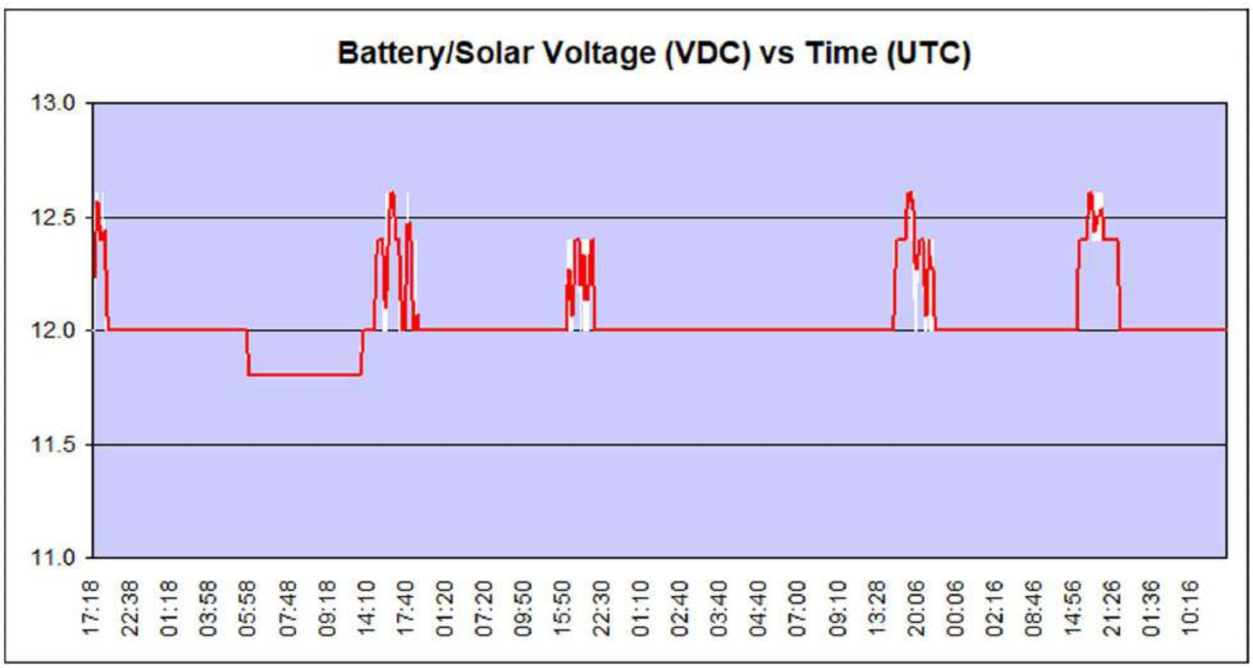


Figure 6: Battery/Solar Voltage Monitoring

Telemetry-over-WSPR lets me remotely monitor my RV trailer's solar/battery power supply voltage levels and charge/discharge cycles.

My Final

In part 2, I switch to QRP Labs awesome “Ultimate” Arduino Uno transmitter shield using an Si5351 DDS with the add-on TCXO (optional and highly recommended) along with my custom encoding Arduino program and decoding spreadsheet included in the supplement zip file for this article, which you should be able to easily modify it for your own telemetry-over-WSPR project(s).—73

References and Resources

Hojo Ham Blog https://tinyurl.com/mrketpfk

JTEncode Arduino Library https://tinyurl.com/yckuxsbx

Maidenhead Locator System https://tinyurl.com/2p83u4xj

VE3KCL Information https://tinyurl.com/2yt8kyuz and https://tinyurl.com/224j9bbw

U4B Balloon Tracker (QRP Labs) https://qrp-labs.com/u4b.html

Ultimate Arduino Uno Shield Transmitter Kit https://tinyurl.com/378hcked

QRP Labs Balloon Tracking http://qrp-labs.com/tracking

WSJT-X https://tinyurl.com/bdeb57w9

WSPR Wiki https://tinyurl.com/2p82f2nm

WSPRnet www.wsprnet.org