TAPR Magnetometer RF Exposure Testing

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Introduction

The magnetometer being developed by TAPR for use as part of a Personal Space Weather Station is often going to be installed in a ham's back yard, where we usually will find an "antenna farm." Many hams don't have acres to spread out in, so magnetometers will be in the vicinity of antennas used for transmitting. This report covers the results of a series of tests intended to explore if (and how) a magnetometer will be affected by nearby transmissions in the commonly used ham bands, plus results of checking for RF (noise) being radiated by the magnetometer itself.

The issue

The recommended installation configuration for a magnetometer is in a sealed PVC pipe buried vertically down to a depth of 24 inches (61 cm) below grade. From the magnetometer to the indoor monitoring point (typically a Raspberry Pi [R-Pi] single-board computer, or SBC) runs a shielded CAT6 cable. The CAT6 cable is grounded (only) at the SBC. The concerns are:

- How local RF might affect magnetometer readings or the operation of the device
- How do the relative locations of the antennas and magnetometer make any interactions between them more or less strong
- Does the magnetometer and/or its cable radiate any RF noise that could impact the operation of the amateur radio station, particularly in the case of low-signal work?

Test setup

Two magnetometers were installed, buried as recommended at two locations relative to a variety of antennas; see Figure 1. Each magnetometer was connected to its respective base board on a (separate) Raspberry Pi in the shack via a shielded CAT6 cable grounded at the R-Pi.

Figure 2 shows the recommended magnetometer in-ground installation in 1-1/2" PVC pipe. The bottom cap is glued on using PVC cement; other joints are sealed with silicon seal to allow for disassembly. The magnetometer itself is wrapped in bubble wrap to center it (a newer design is now being developed with a 3D printed centering bracket for the magnetometer).

Figure 1. Layout of test area, showing antenna and magnetometer locations; approximately to scale.

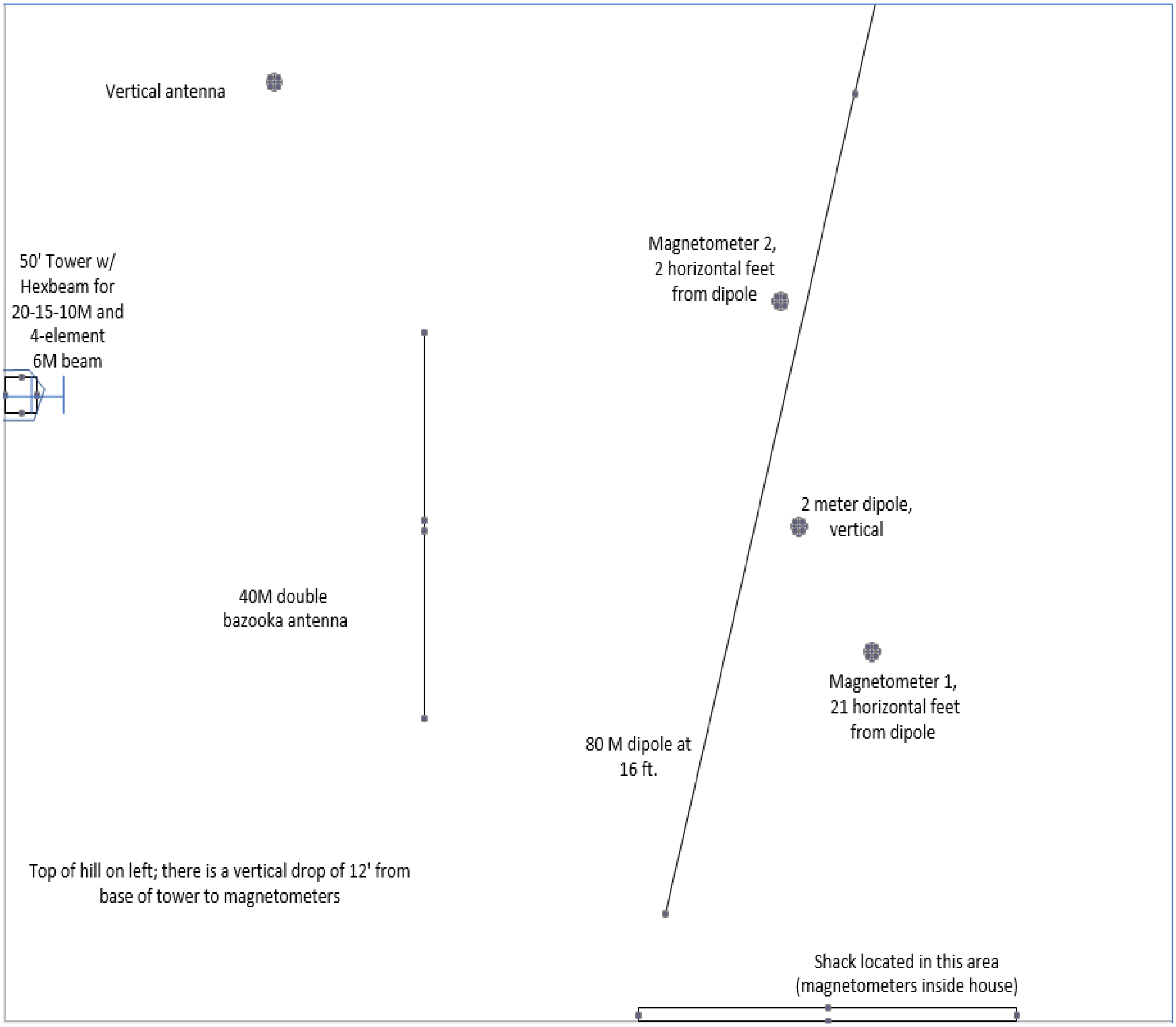
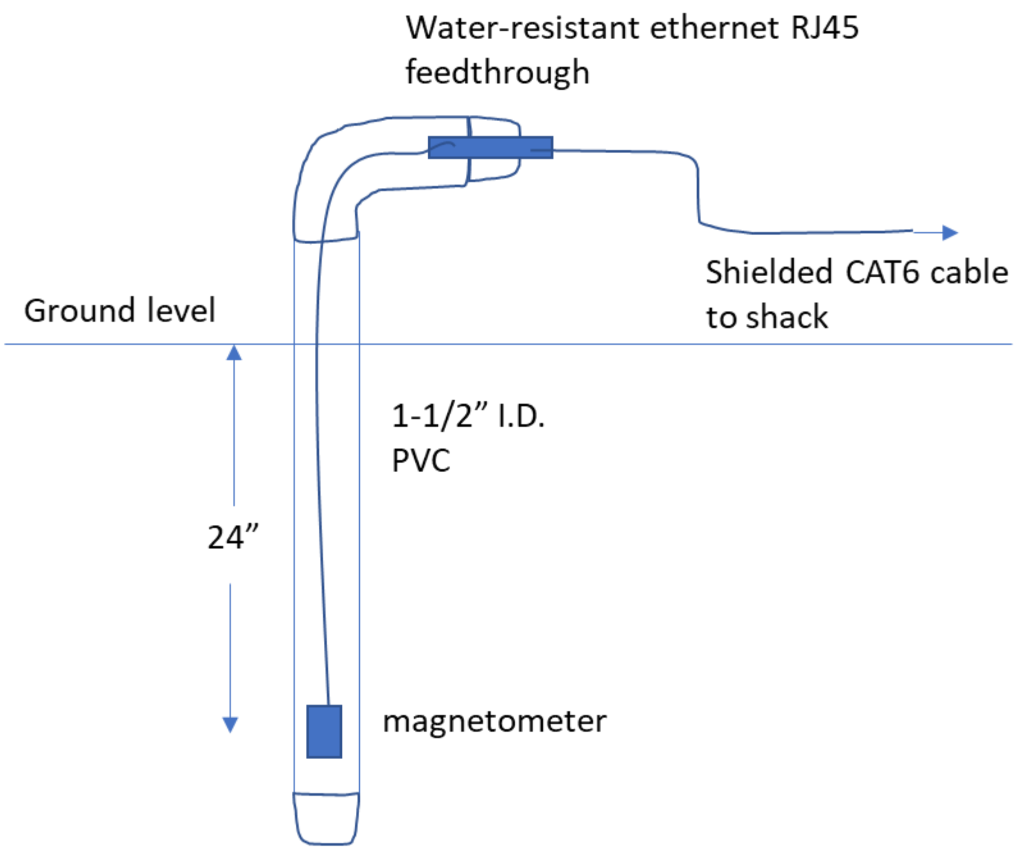


Table 1. Distances from various antennas to magnetometers.

Distance to	Antenna for wavelength(s), meters	mag1 (feet)	mag2(feet)
Top of tower	6, 10, 15, 20	100	100
Middle of double bazooka	40	43.5	43
Base of vertical	160	68.5	52
80 M dipole	80	25.6	16.1
2 M dipole	2	11	24

Figure 2. Magnetometer in-ground installation.



RF Exposure Test method

A series of tests were run, collecting data from the magnetometers over a 3 minute test period, where the first minute was background (transmitter off), the second minute was RF exposure (transmitter on), and the third minute background again (transmitter off). Taking two background measurements(before and after every RF exposure period) allows us to compensate for natural changes in the earth’s magnetic field during the test, when analyzing collected data: the combined background readings were compared with the readings during RF exposure.

On each band, three tests (of 3 minutes each) were run, with straight carrier, CW at 15 wpm, and SSB transmission; this was done with both magnetometers. The bands used for testing were 160, 80, 40, 20, 15, 10, 6, and 2 meters. RF power levels were limited by the amount of power available at the AB4EJ station: 1 KW to 1.5 KW on 160 through 10 meters, 500 W on 6 meters, and 50 watts on 2 meters.

Magnetometer data was collected at about 1 reading per second using the runMag program developed by Dave Witten, KD0EAG. The following command was used:

```
sudo ./runMag -M 23 -A 10 -U 140 -Z | tee ./log3/filename.csv
```

Meaning of the parameters:
-M 23: the R-Pi being used here selects I2C address 23 for the magnetometer, so this is used to address it
-A 10: NOS value recommended by magnetometer team
-U 140: delay in mSec before data ready; recommended by magnetometer team
-Z : commands the magnetometer to include the total magnetic field (“Tm”) in its output

This outputs an approximately 1 per second comma separated variable data line, which routes to stdio (the screen), and using the pipe (“|”) is sent by tee also to the file (filename.csv). A typical data line looks as follows:

```
"06 Jul 2021 00:00:00", 26.25, 28.69, 3938.7, 2569.3, -146.7,
2954, -1927, -110, 4704.89957
```

Values are time stamp, external temperature (deg. C), internal temperature (deg. C), x, y, z, raw x, raw y, raw z, and total magnetic field.

Regarding units: the units output for x, y, z and T_m with this command are micro-Teslas multiplied by 100. This requires an additional math step for comparison with commercial magnetometers, but since this project is focusing on relative changes (rather than directly comparable absolute numbers) this is being used as it comes from the runMag program, for simplicity.

Each test run produced about 180 lines of data during the 3 minute test (60 lines each of background, RF-exposed, background).

Data Analysis

Technique

Data from the x and y axes were analyzed, since the z axis is aligned as closely as possible with earth field and is a very small value. Data from all bands tested was collected individually from the two magnetometers.

For each analysis, the readings from “before” and “after” background were combined to form a total background against which to compare the readings with RF activated. Previous informal testing had shown that RF effects on magnetometer readings would, in most cases, be so small that viewing data with the naked eye (i.e., looking at a graph of the readings) would not reveal anything; it would be necessary to use a statistical technique to look for effects. The process was designed as follows:

- Assume that the earth’s magnetic field changes slowly enough so that the mean (“average”) value of axes x and y would remain stable over a 3 minute test period.
- Compare the mean field values for the RF-exposed test data to the combined “before” and “after” background field mean.
- Use a two-tailed t-test (“Student’s t”) as follows, for each set of test values:
    - The combined background field values form Population 1; the RF-exposed values form Population 2
    - The (“null”) hypothesis is that there is zero difference between the means of Populations 1 and 2

- The t-test produces a t Statistic which is compared to the critical t value ("t Critical") for the test. Use a 95% confidence value from the t Critical table.
- If the absolute value of the t Statistic exceeds t Critical, the null hypothesis is disproved; that is, we are 95% confident that there is a difference between the mean values of that axis's readings between background and under RF exposure. (This is commonly called a "statistically significant" difference).

Results

It was found that exposing the magnetometer to RF causes one of these outcomes:

- No statistically significant effect on magnetometer readings (76 results)
- A statistically significant effect on magnetometer readings (16 results)
- Halting of magnetometer (4 results)

There were no instances where RF damaged the magnetometer.

Tabular results are shown in tables 2A and 2B. The highlighted boxes show where there was a statistically significant difference in magnetometer reading during RF exposure (i.e., t Statistic exceeds t Critical). Those blocks containing "fail" indicate that the RF exposure was so high that it stopped the magnetometer from working (probably due to disruption of I2C communication).

Table 2A: Results of Magnetometer 1 RF Exposure by Band and Emission Type

		Magnetometer 1 (mag1")					
		X axis			Y axis		
		Carrier	CW, 15 wpm	Phone	Carrier	CW, 15 wpm	Phone
160M	t Statistic	5.293	1.794	-0.878	0.600	-0.744	1.486
	t Critical	1.982	1.983	1.982	1.981	1.983	1.983
80M	t Statistic	-0.956	1.794	0.412	3.128	-0.744	-0.388
	t Critical	1.982	1.983	1.988	1.981	1.983	1.994
40M	t Statistic	0.495	3.708	-1.469	2.126	2.279	-0.260
	t Critical	1.981	1.978	1.986	1.987	1.978	1.990
20M	t Statistic	0.535	1.921	-2.925	0.054	0.516	0.377
	t Critical	1.981	1.983	1.981	1.977	1.982	1.977
15m	t Statistic	1.505	-0.641	0.137	-0.858	1.330	0.819
	t Critical	1.985	1.985	1.986	1.988	1.989	1.983
10m	t Statistic	-3.553	1.991	0.033	1.570	2.082	-0.961
	t Critical	1.983	1.982	1.979	1.980	1.991	1.986

6M	t Statistic	1.112	1.337	0.445	0.898	0.275	-0.041
	t Critical	1.984	1.977	1.979	1.992	1.985	1.982
2m	t Statistic	0.222	-0.680	-1.953	-0.193	-0.929	0.956
	t Critical	1.981	1.983	1.980	1.980	1.983	1.983

Table 2B: Results of Magnetometer 2 RF Exposure by Band and Emission Type

		Magnetometer 2 ("mag2")					
		X axis			Y axis		
		Carrier	CW, 15 wpm	Phone	Carrier	CW	Phone
160M	t Statistic	-0.383	-0.738	-0.462	0.000	-0.279	1.057
	t Critical	1.986	1.984	1.978	1.983	1.985	1.989
80M	t Statistic	23.690	fail	fail	18.142	fail	fail
	t Critical	1.986			1.990		
40M	t Statistic	3.203	0.703	1.004	-1.110	-0.786	-0.169
	t Critical	1.983	1.984	1.987	1.980	1.981	1.983
20M	t Statistic	1.450	1.208	1.673	-0.347	1.305	-2.583
	t Critical	1.986	1.984	1.984	1.983	1.982	1.984
15m	t Statistic	-1.101	-1.096	-0.104	-0.230	-0.516	1.144
	t Critical	1.978	1.982	1.986	1.983	1.984	1.984
10m	t Statistic	-0.319	0.221	2.638	-1.446	-0.328	-1.738
	t Critical	1.986	1.980	1.986	1.981	1.982	1.984
6M	t Statistic	0.658	-3.121	-1.581	-1.003	0.741	1.221
	t Critical	1.979	1.985	1.979	1.980	1.987	1.984
2m	t Statistic	-2.068	0.850	-1.263	-0.249	-1.168	0.734
	t Critical	1.981	1.987	1.979	1.987	1.975	1.989

Out of 96 tests, there were:

- 76 tests where RF exposure did not affect magnetometer readings
- 16 tests where RF exposure appears to have affected magnetometer readings
- 4 tests where RF exposure caused magnetometer data collection to halt (until RF was turned off)

These results do not necessarily indicate a problem, or any serious limitation on the magnetometer's use; some visualizations and further analysis show why this is so.

Analysis of Results and Visualizations

When considering the results in Table 2, an active ham (i.e., frequently on the air) will ask, "will my on-air activity seriously corrupt the magnetometer data I am trying to collect?" To answer this question, we first look at the magnitude of the RF-driven data effects (when manifested as a statistically significant change in the mean magnetometer readings when RF-exposed). Refer to Table 3 (note that those tests where RF actually shut the magnetometer down are not included in this table).

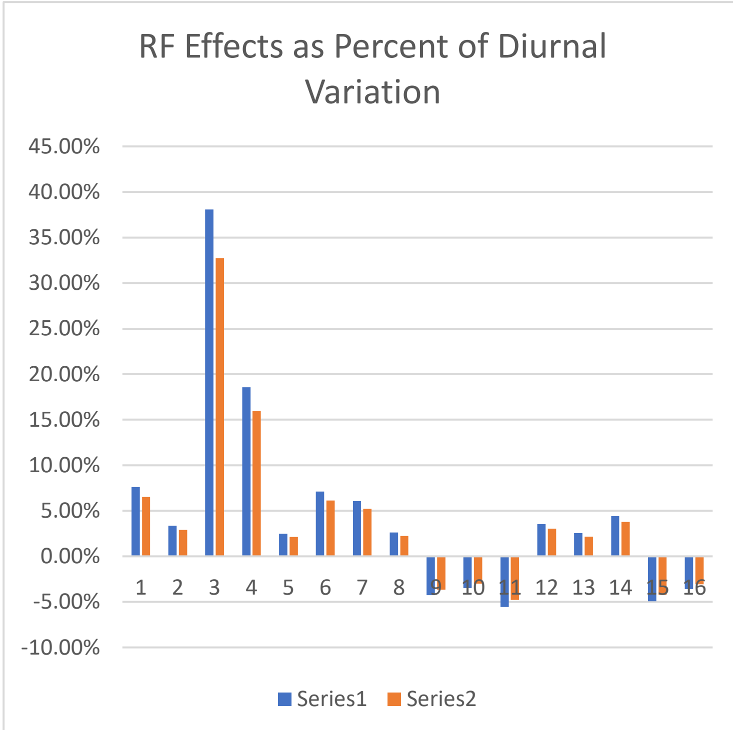
Table 3. Magnitude and Percent Differences in RF-affected magnetometer readings

	Band,Emission,Device,Axis	Mean (no RF)	Mean (RF)	delta	percent delta to base value	percent delta to diurnal excursion X	percent delta to diurnal excursion Y
1	160M carrier, mag1, X	4062.298	4061.691	0.607	0.0150%	7.59%	6.53%
2	80M carrier, mag1, Y	2289.424	2289.155	0.269	0.0118%	3.36%	2.89%
3	80M carrier, mag2, X	4008.670	4005.625	3.045	0.0760%	38.06%	32.74%
4	80M carrier, mag2, Y	2193.214	2191.730	1.484	0.0677%	18.55%	15.96%
5	40M carrier, mag 1, Y	2289.230	2289.030	0.199	0.0087%	2.49%	2.14%
6	40M carrier, mag2, X	4008.571	4008.002	0.570	0.0142%	7.12%	6.12%
7	40m CW, MAG 1 , X	4052.100	4051.615	0.485	0.0120%	6.06%	5.22%
8	40M CW, MAG 1 , Y	2280.425	2280.217	0.208	0.0091%	2.60%	2.24%
9	20 fone, mag 1, X	4061.865	4062.207	-0.342	-0.0084%	-4.28%	-3.68%
10	20 fone, mag2, Y	2192.409	2192.687	-0.278	-0.0127%	-3.48%	-2.99%
11	10M carrier, mag1, X	4061.915	4062.361	-0.446	-0.0110%	-5.57%	-4.79%
12	10M CW, mag1, X	4061.677	4061.394	0.283	0.0070%	3.54%	3.04%
13	10M CW, mag1, Y	2289.242	2289.039	0.203	0.0089%	2.53%	2.18%
14	10M fone, mag2 X	4008.425	4008.074	0.352	0.0088%	4.40%	3.78%
15	6M CW mag2, X	4007.484	4007.877	-0.394	-0.0098%	-4.92%	-4.23%
16	2M carrier mag2, X	4007.664	4007.950	-0.286	-0.0071%	-3.58%	-3.08%

The rightmost 2 columns show the maximum RF effects as a percentage of the typical diurnal variation of the fields, being approximately 8 and 9.3 for x and y, respectively.

The changes to readings (except for lines 3 and 4) show an impact to magnetometer readings as <= 7.6%. A histogram, Figure 3, shows this table as follows:

Figure 3. Histogram showing percent error introduced by RF; based on data from Table 3.



The RF effects (when there are any) range from about -6% to +7.6%, except for the outliers in lines 3 and 4. Now the questions are (a) what is special about lines 3 and 4, and (b) what does a difference of +/- 7.6% mean in impact to magnetometer data?

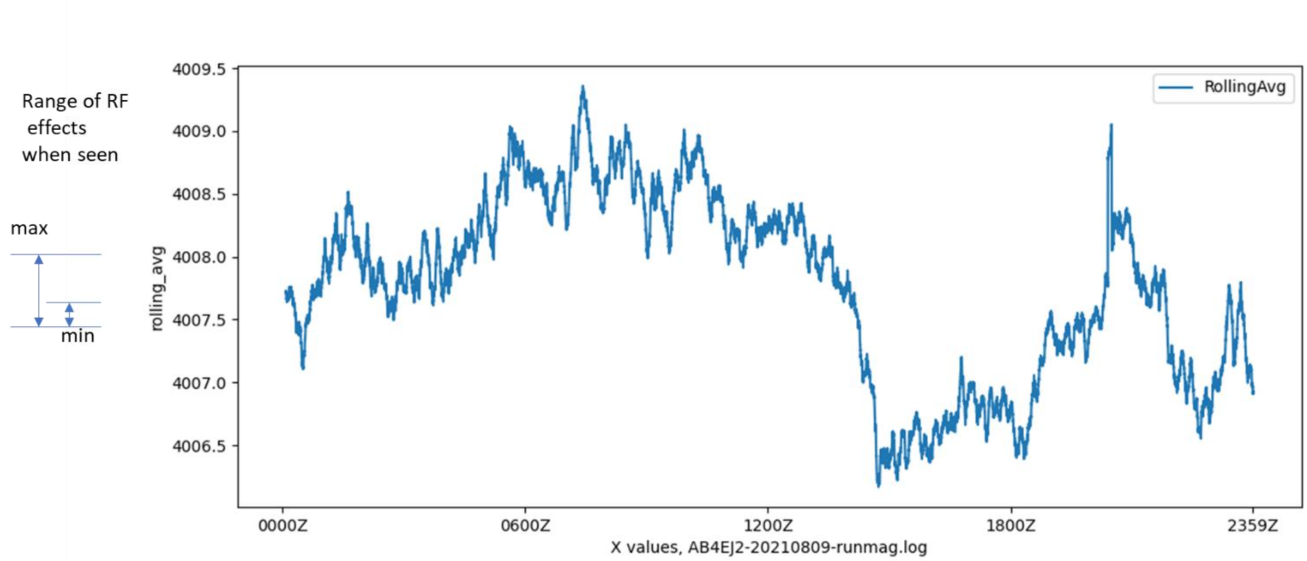
For question (a), Figure 4 shows the problem with magnetometer 2 on 80 Meters: the magnetometer is buried almost directly underneath the 80M dipole; at 1500 watts, the RF field is strong enough to penetrate down to the 24" depth of the magnetometer. This shows an example of what not to do, and can be remedied by moving the magnetometer further away from the antenna.

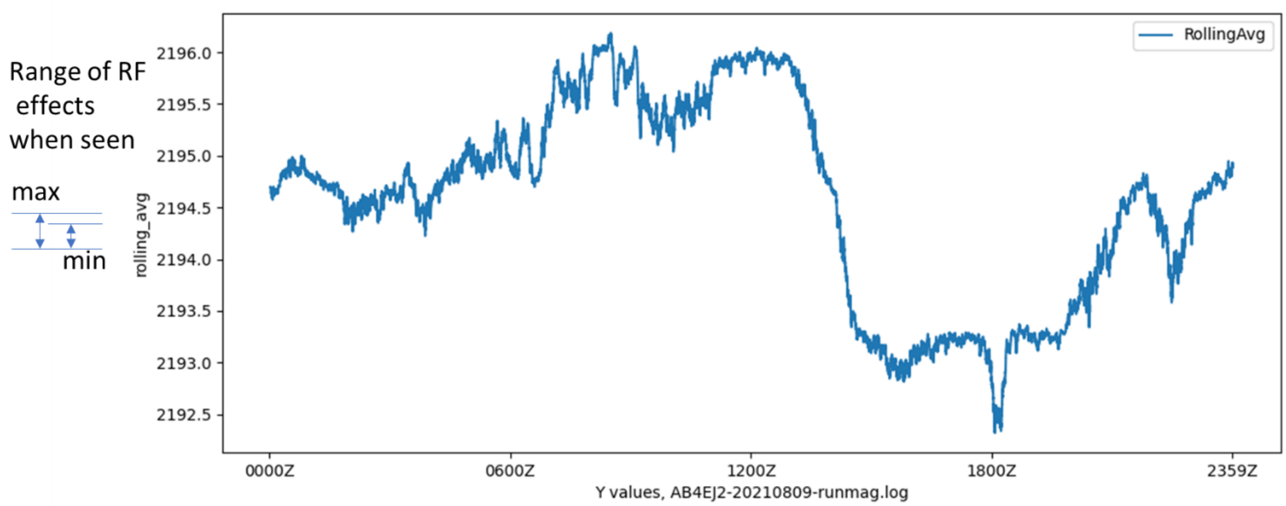
Figure 4. The 80M dipole is shown in false color to distinguish it from the trees; a red arrow points to magnetometer 2, installed in the worst possible location.

This is not a surprising result; magnetometer 2 was intentionally placed at this “bad” location (about 16 feet from the dipole) to quantify how much RF it would take to disturb it. Note: when the power to the dipole is limited to 100 W, we do not see a statistically significant RF impact; but we do see effects at 200 W and up.

Now, what about question (b): will a +/- 7.6% difference in magnetometer reading corrupt the analyses we are trying to do? Figure 5 shows one day of monitoring magnetometer 2, axes X and Y, with **no** RF exposure.

Figure 5. 24-hour plots of X and Y axes on magnetometer 2, with no RF exposure.





We can see that the earth field excursions in X and Y are approximately 3 and 4.5 units in these charts, respectively (much larger than the RF impacts) The background magnetic field can range up to 20 units from center, or more in both x and y. The max/min note on each plot shows the amount of error that would be introduced by the *typical* impactful RF exposure measured in any of the tests (here, the RF effect of 1.5 kW on 80M on magnetometer 2 is omitted, as RF definitely swamps the earth's field when the magnetometer is directly under the antenna at high power). By inspection, we can see that, even though strong RF may cause a small "glitch" in tracking the trend line of the earth's magnetic field, it is not enough to change the *overall shape* of the trend lines (where we are monitoring the trends for events such as a geomagnetic storm). Other researchers have found that other events that affect the magnetic environment around a magnetometer, such as parking a car near it, have a comparable or larger effect. Clearly, if you place a magnetometer within 20 feet of an antenna transmitting with high power, your data output will consist of mostly noise during transmit periods; but with careful placement of your magnetometer and some testing, you can feel confident in the validity of your data even when your station is active.

Is it really necessary to use a statistical approach?

Using a t-test for this may seem like an unnecessary complication; but consider the following. In cases like the 80M dipole being very close to the magnetometer, the impact of RF is clear even when all you do is plot the data, such as in Chart A of Figure 6, below.

Figure 6. Comparing plots of data.

Chart A

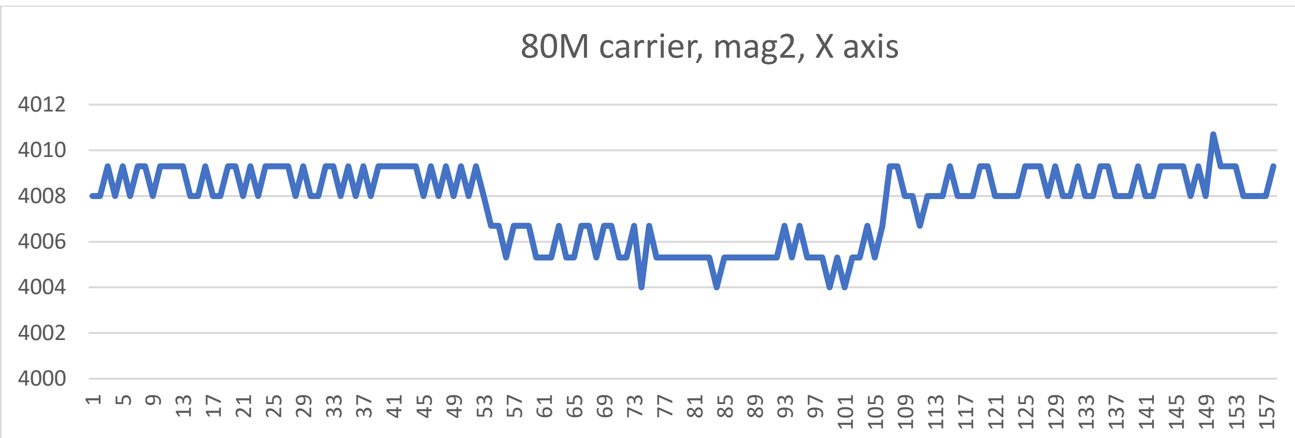
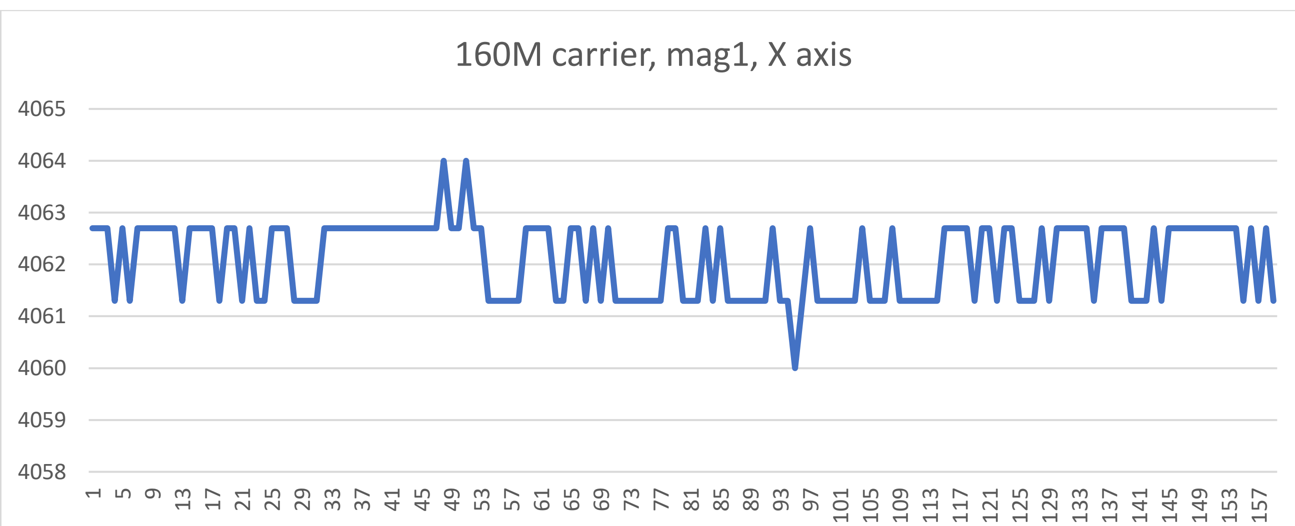


Chart B



In Chart A, it is easy to see that the magnetometer values change dramatically when RF is applied at about 55 seconds into the run and removed at 103 seconds. But what about Chart B? There is not an easily-discerned difference in the signal between seconds 60 and 120.

As it happens Chart B also has a statistically significant difference in the signal between RF on (60 seconds to 120 seconds),with a delta of about 0.6 units. This won't affect the overall shape of the resulting diurnal plot, but might be confused with a short solar event.

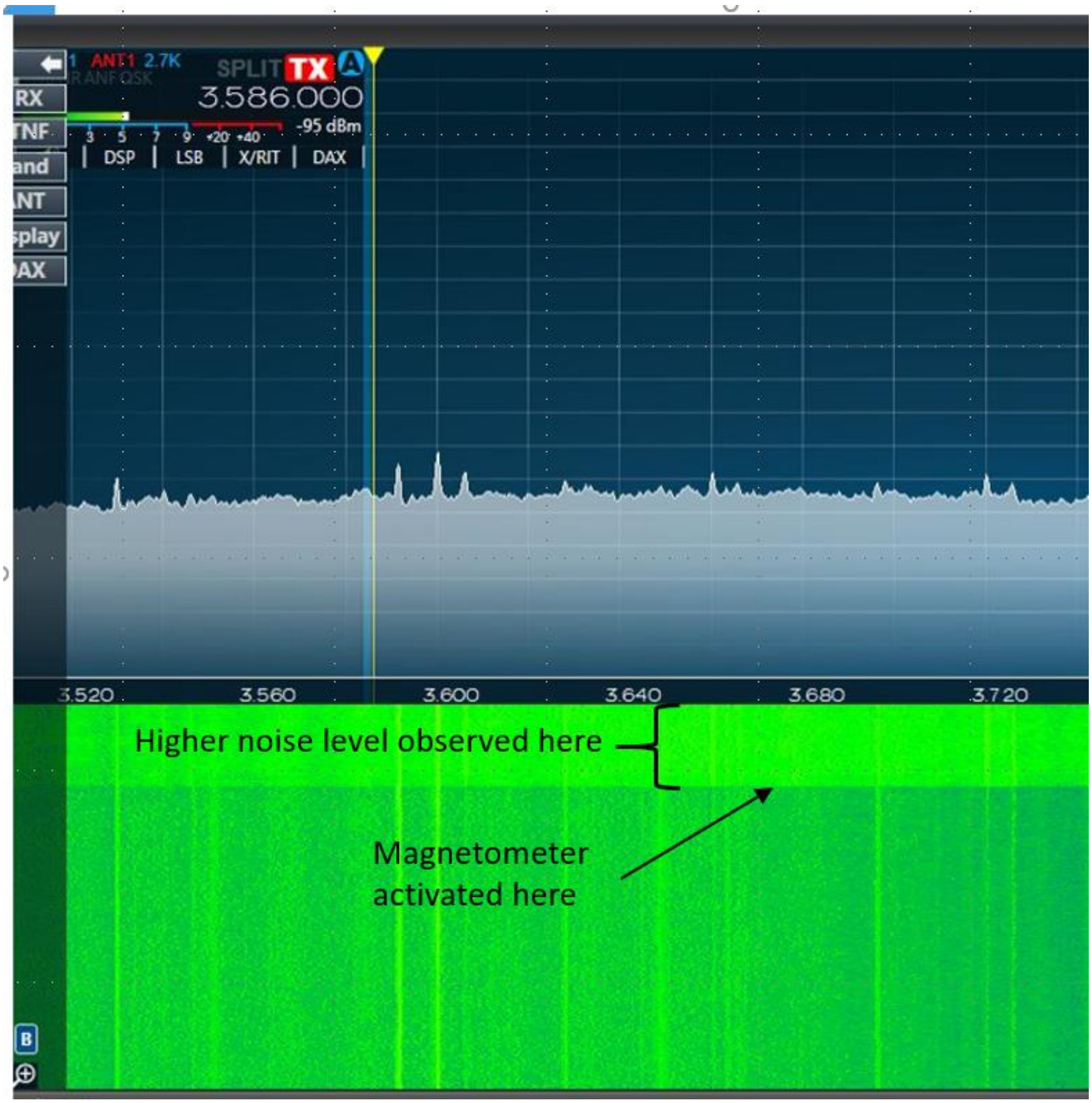
Testing magnetometer for radiated RF noise

In keeping with the concept of making the magnetometer compatible with a typical ham radio installation, the magnetometer was tested to look for any RF noise radiation. For this, a FlexRadio 6600 was used to watch the waterfall for signals or noise created by the device. The same ham bands were examined as used for the RF exposure testing.

The test consisted of observing each band at a relatively quiet time, turning the magnetometer on and off, and looking for noise or signal to appear and disappear with magnetometer activation.

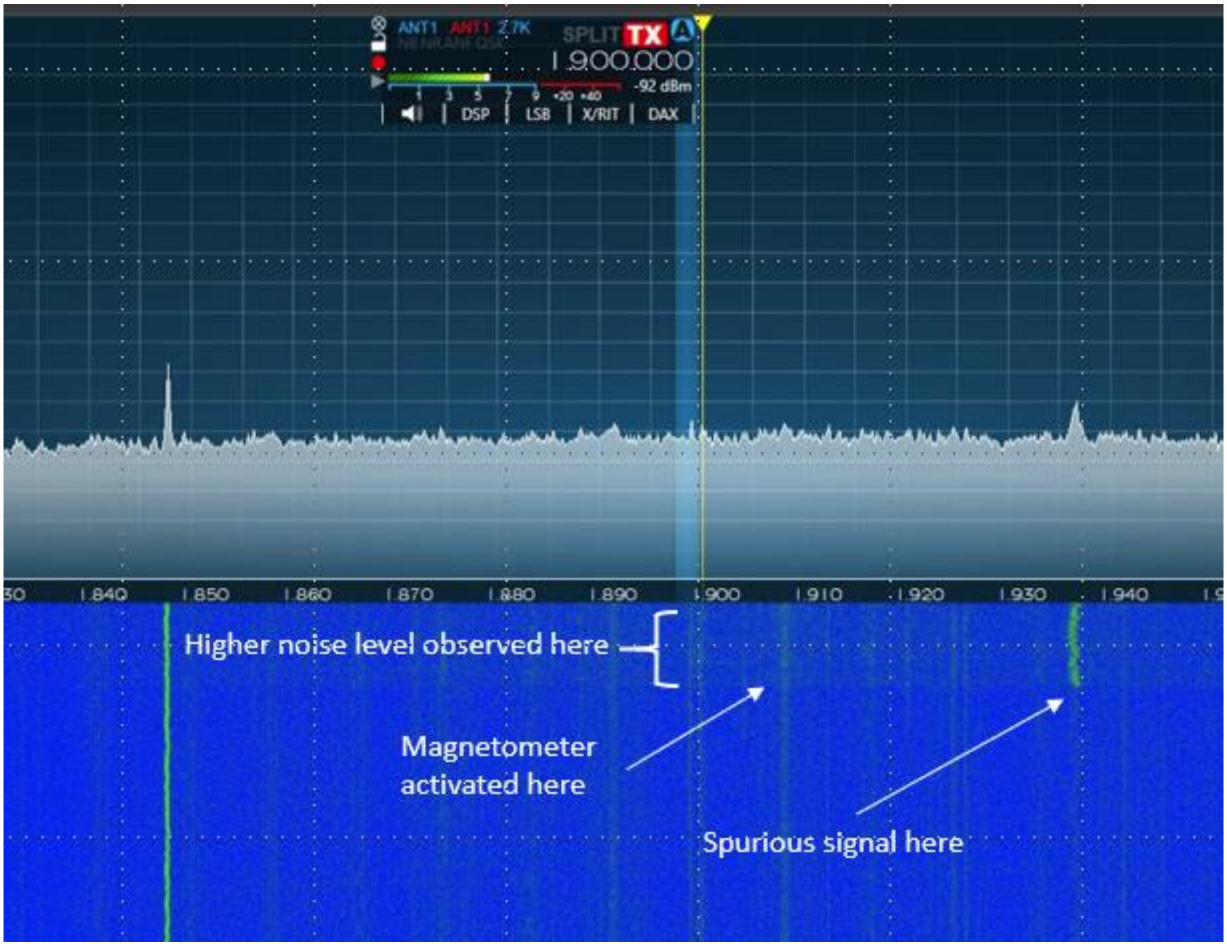
On most ham bands, no noise or signal was observed with magnetometer activation; however, with 80 meters, a noise of 2 to 3 s-units was observed; Figure 7.

Figure 7. Noise observed on 80M.



On 160M, an increased noise level of about 1 to 1.5 s-units was noticed, along with a signal ("birdie") on 1.935 MHz; Figure 8.

Figure 8. Noise and spurious signal on 160M.



The sources of these noises were identified:

- The Raspberry Pi was being operated ungrounded, which allowed the shield of the CAT6 cable to float.
- A switching power supply (i.e., the one that came with the Raspberry Pi Canakit) was adding noise to the system, which was radiated from the CAT6 cable and/or the magnetometer and/or the R-Pi itself.

These noises were eliminated by two modifications to the system:

- Replaced the switching power supply with a linear power supply.
- Grounded the R-Pi. The R-Pi has a built-in sound card with the jack sleeve being connected to the R-Pi ground. A 1/8" plug was installed with only the outer sleeve connected to a cable run to shack earth ground.

Both the wide-band noise and the spurious signal birdie were then eliminated.

Summary & Recommendations

Conclusions

- It is possible to disturb the readings of a magnetometer with nearby RF, particularly when running high power levels.
- However, the effects are small relative to the natural changes in the earth's magnetic field. (In fact, in a number of cases where there was a statistically significant change to the readings, the effect was so small that we cannot rule out the possibility that the "effect" was simply normal drift in the earth's magnetic field that occurred during the test.)
- RF effects on magnetometer readings do not appear to be large enough to swamp out the diurnal variation in the earth's magnetic field, but further research is needed to determine if RF effects could mask more subtle magnetic signals such as those produced by a geomagnetic storm or solar coronal mass ejection.

Recommendations

It is possible to **minimize the effects of RF** on magnetometer readings by:

- Siting the magnetometer as far away from transmitting antennas as practicable
- Running lower transmitter power levels (100 W or less) (no statistically significant RF effects were seen at 100 W even in the worst case situation, i.e., magnetometer 2, directly under the 80M dipole), while collecting data

You should **characterize your magnetometer** using the test method described above, after you have it in a location as far as possible from your transmit antennas.

If you wish to avoid noise from the magnetometer power supply and cable getting into your receiver, **use a linear power supply** (instead of the switching power supply that usually comes with the R-Pi), and **ground the case** of the R-Pi. Use shielded CAT6 cable, grounded at the R-Pi end.

Future work. We need to do some further research and tests; for example, we need to study magnetometer plots and look to see what signatures we see in the data when a geomagnetic event occurs, and compare these to what we see in the same type of plots on, say, a contest weekend, when the local ham station is running high power for an extended period of time. Also, we should try locating a magnetometer at various distances from the transmit antenna and see how far away it actually needs to be to eliminate RF effects even when running 1500 W (this will require a large test space).

Acknowledgements

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