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Doppler Tracking

The author combines some simple electronics with a physics principle to measure speed and height of his model rocket launches.

The "Doppler effect" is responsible for frequency shifts of the received signal just by virtue of movement of the reflecting or transmitting source.[1] It almost seems like you get something for nothing. By this I mean that no complex electronics are required to produce the frequency shift, and those that are required are familiar to the typical ham operator. The system that I will discuss uses some of my ham equipment.

Most applications of the Doppler frequency shift have one thing in common: the object being measured is moving. These applications include radar to track incoming storms or fast moving motorists, medical applications to measure blood flow in arteries and veins, and astronomy applications to measure the speed of stars moving toward or away from Earth. Although the frequencies used, be they audio, RF, or optical, may differ for each application, the effect is the same.

But what can Joe Ham do with the Doppler effect? My own interest in using the Doppler effect comes from a secondary hobby, model and high power rocketry. Do you think you have too many hobbies? While attending rocket launches at the Black Rock desert in Nevada, I all too often observed rockets that would make great ascents but have ballistic descents caused by parachute deployment problems. The result was a destroyed rocket and, electronics embedded in the desert floor. The thought occurred to me that if these rockets had some sort of inexpensive and sacrificial RF system, in case of a crash, maybe we could learn something about the speed and altitude of these imperfect flights.

I didn't want the project to be so sophisticated that it required extremely high RF power levels or specialized tracking antennas. For example, Doppler weather radars use many kilowatts of power. I was more interested in milliwatts. I did not consider a transponder because I thought it too complex. I was after simplicity. There was some previous work on transponder systems done by Steve Bragg, KA9MVA. Steve referred to his experimental work as the "Digital Amateur Rocket Tracking System."[2] I also wanted to make use of ham radio equipment I already owned or could easily build. I decided early on to make use of the 23 cm band, and this decision was primarily based on owning an older ICOM IC-1271, which is a multi-mode 23 cm. transceiver. The SSB mode was very important to make these measurements, as this mode produces a tone from a CW signal. I was already familiar with the 23 cm band since I had worked ATV and FM repeaters on that band. It helps with Doppler to use as high a frequency as possible, since the Doppler frequency shift is proportional to the operating frequency.

So, is the 23 cm band high enough in frequency to make some measurements? We shall see.

Theory

The Doppler shifted frequency is given by this formula:

$$f_{rec} = f\,(1 + v/c) \qquad \text{[Eq 1]}$$

where:

f is the transmitted frequency

f_{rec} is the frequency of the wave arriving at the receiver

v is the velocity of the transmitter relative to the receiver in meters per second.

(v *is* positive when the transmitter and receiver move towards one another and negative when they move away from each other)

c is the speed of the wave (3×10^8 m/s for electromagnetic waves traveling in air or a vacuum)

Δf is the Doppler frequency shift.

This equation assumes that we are using radio frequencies that propagate at the speed of light, and that the relative velocities of the transmitter and receiver are a small percentage of the speed of light. These are good assumptions for the applications I had in mind.

What kind of frequency shift can we expect for 23 cm signals? For a velocity v = 25 m/s — which is about 56 mph — a frequency shift of 108 Hz should result. Is this enough shift? Do we need higher speeds? Do we need higher frequencies? Frequency stability ultimately determines the frequency resolution and thus velocity resolution of the measurement. It turns out 100 Hz is enough shift for short-term — 1 minute or less — measurements. At 1200 MHz, 100 Hz corresponds to a stability of 0.08 parts per million (ppm). Modern transceivers, particularly those designed for SSB and CW, have stability specifications of at least 3 ppm. For example, my older IC-1271 has a stability

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[1] Notes appear on page 37.

of 3 ppm, and a newer transceiver like the IC-9500 has 0.05 ppm stability. I have found the short-term stability, particularly when the temperature is constant, is much better than the specified values. The specified values assume long-term measurements over a 50°C temperature range.

Hardware and Software

Figure 1 shows a simple experiment. The transmitter and receiver are close enough so the receiver can hear the transmitter at the low desired power levels. The car can be driven away from the receiver for one test and toward the receiver for another test. We need a receiver with SSB capability because we are basically tracking the tone produced in the receiver as it hears the unmodulated carrier from the transmitter. This is the same tone you hear when you listen to someone tune their transmitter. The bandwidth of most SSB receivers can handle the expected velocities and corresponding Doppler frequency shifts. For example a 2.4 kHz bandwidth, typical for an SSB receiver, would allow velocities as great as 581 m/s at 23 cm. Incidentally, Mach 1 (the speed of sound) is 340 m/s at 15°C. I used the previously mentioned IC-1271 for the receiver, but any modern day 23 cm multimode receiver or transceiver would suffice.

The transmitter was custom built, but only because I had some specialized requirements. The transmitter needs only to generate a CW carrier of reasonable spectral purity and low drift. This is fairly easy to accomplish with modern phase-locked-loop circuits and crystal oscillators. The transmitter consists of a crystal reference oscillator, a PLL chip with self contained EEPROM, and a power amplifier chip. Size (23 mm × 100 mm) and power supplied <10 mW are low and allow use of small, lightweight batteries. Figure 2 shows a picture of the transmitter as well as the schematic. Cost, in case the transmitter is lost or destroyed, is low (about $35). The total transmitter weight is 1 oz, including batteries. If the transmitter platform is larger, such as an automobile for example, a larger and heavier transmitter can be tolerated.

I was concerned about transmitter stability under acceleration, particularly the G forces on the 32 MHz crystal oscillator that is the reference for the PLL transmitter. The data from the actual launches, however, looked very similar to predicted velocity profiles from computer programs such as *RockSim*.[3] My conclusion was that G forces and short term temperature effects were not enough of an issue to use more sophisticated reference schemes.

A key requirement for analyzing the Doppler data is a computer program that can measure frequency versus time. This is called a spectrogram. I used a shareware computer program, in fact, called *Spectrogram* to both record as well as analyze the data.[4] This program runs on either a PC laptop or desktop and makes use of the sound card for audio input. The program allows for adjustments of the time window and maximum and minimum frequencies of the spectrogram. The data displayed on the screen can simultaneously be stored to a file by selection with a pull-down menu and a mouse driven record on-off feature. *Spectrogram* also allows replaying or analysis of the previously recorded files. There are probably other programs that can perform this task but I found *Spectrogram* met all my needs.

Procedure for Taking and Analyzing Data

The hardware and software setup for all the applications is as follows:

1) Turn on the transmitter.

2) Turn on the receiver.

3) Tune the receiver VFO until the transmitter is making a pleasant tone somewhere between 800 and 1500 Hz. The frequency of this tone is arbitrary. This is just like tuning in your favorite CW signal.

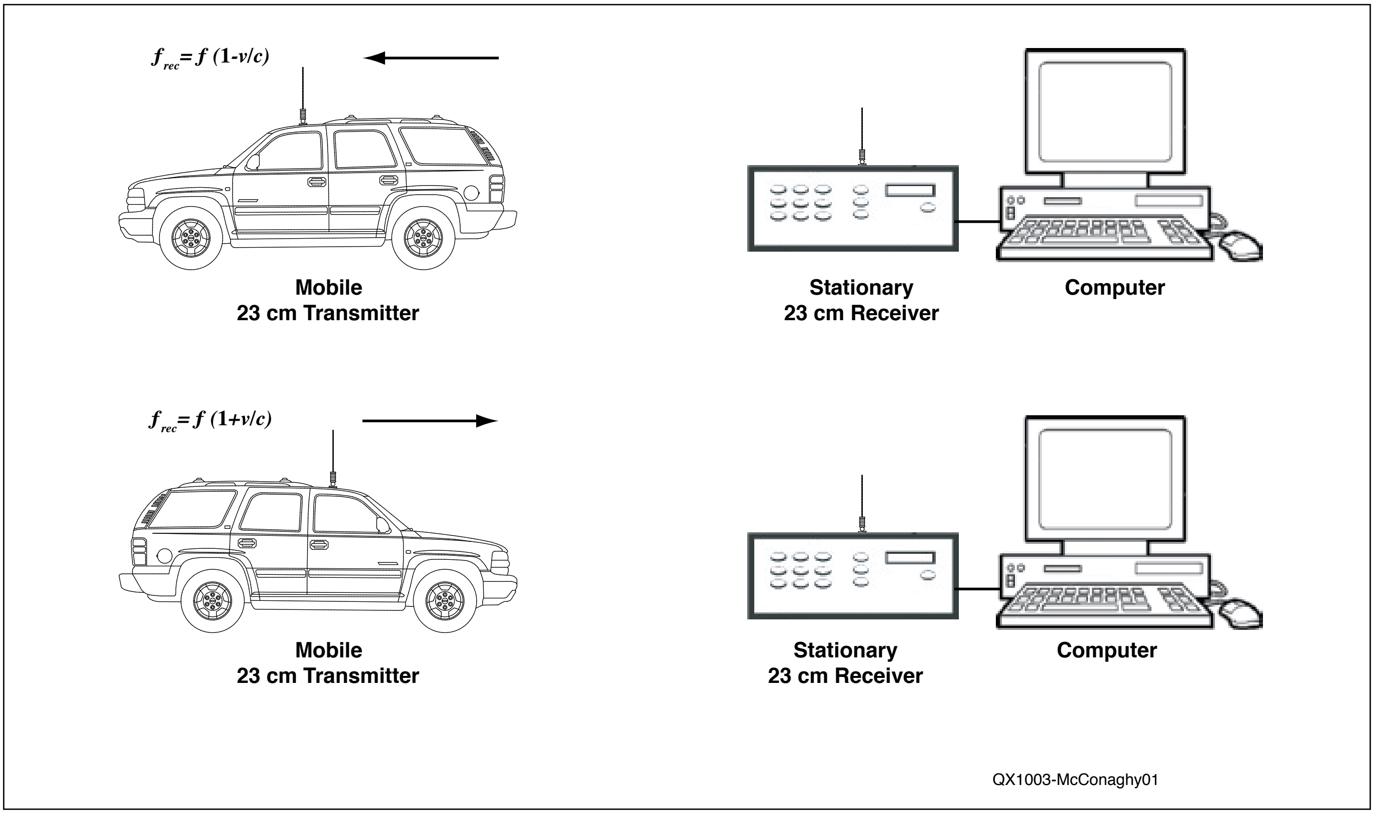
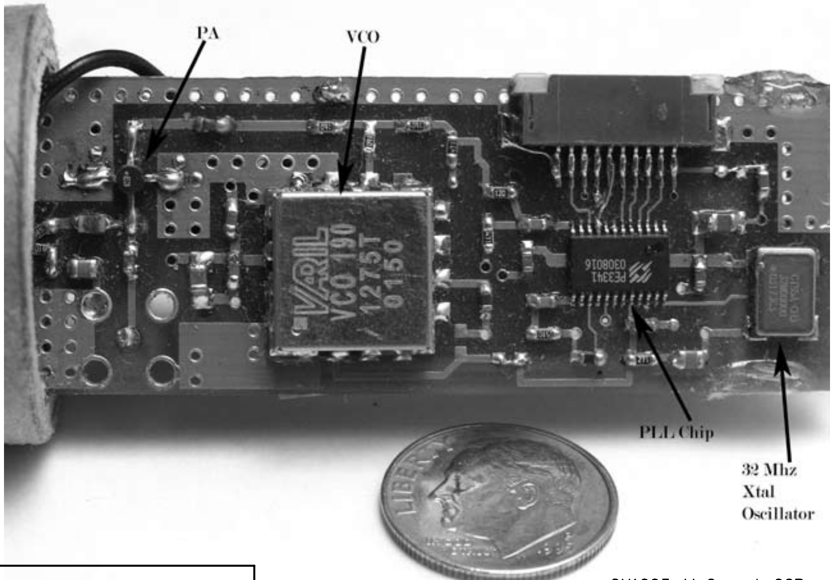
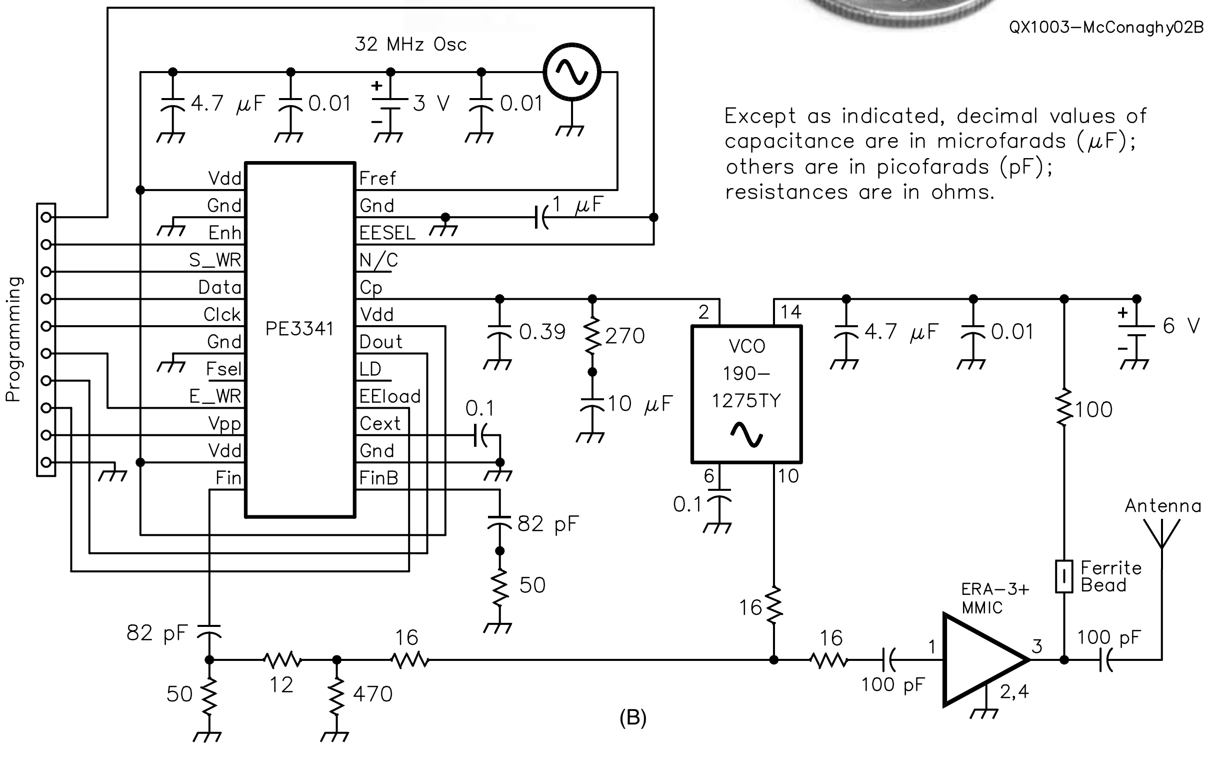


Figure 1 — Drawing showing mobile transmitter moving away from (top) or toward (bottom) a fixed receiver.

Figure 2 — Part A shows the transmitter circuit board, and Part B is a schematic diagram of the transmitter. Part C shows a model rocket, with an expanded photo showing the location of the transmitter board

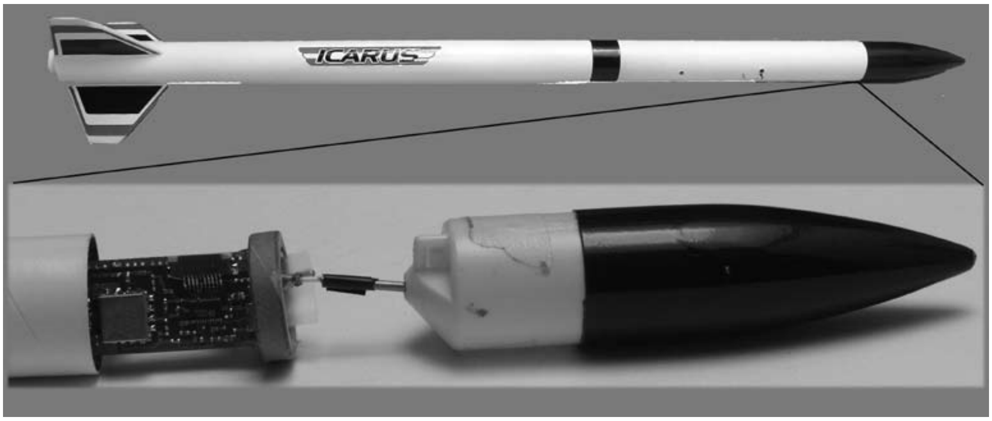


(A)



Except as indicated, decimal values of capacitance are in microfarads (μF); others are in picofarads (pF); resistances are in ohms.

(B)



(C)

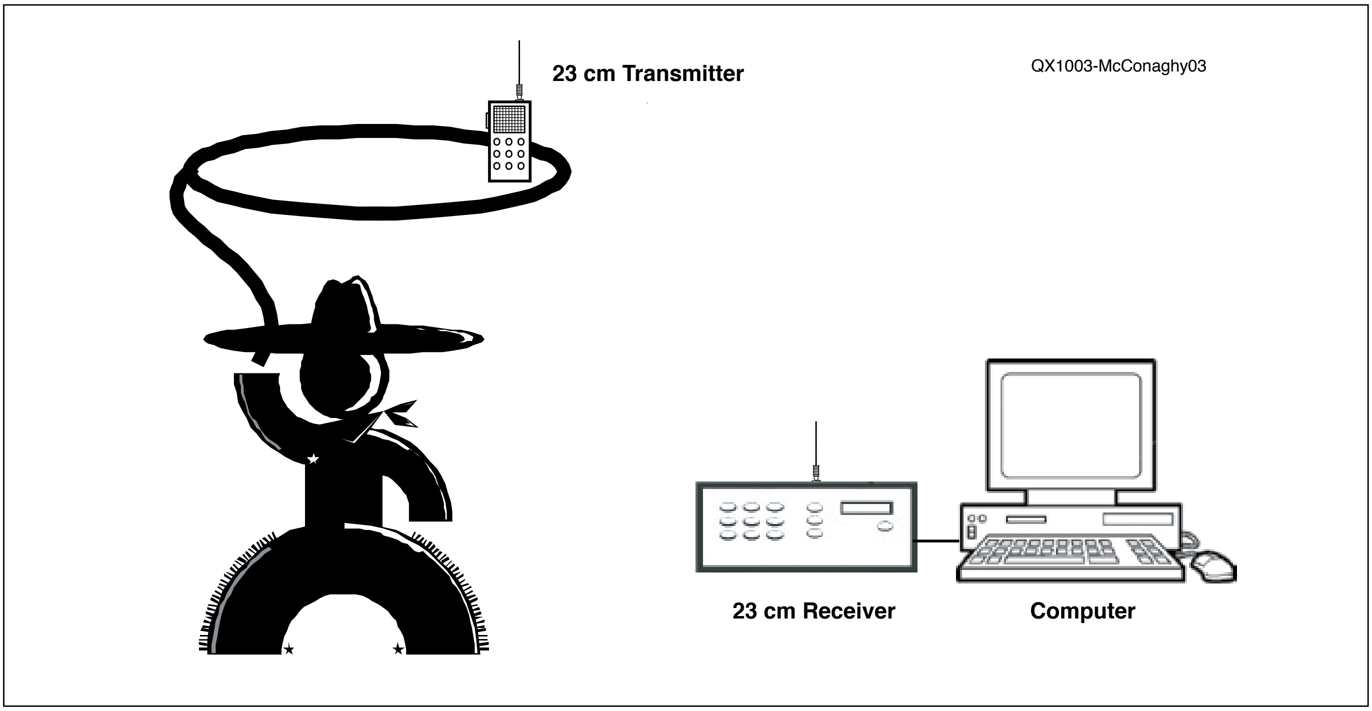


Figure 3 — This drawing shows a transmitter spinning on the end of a lasso.

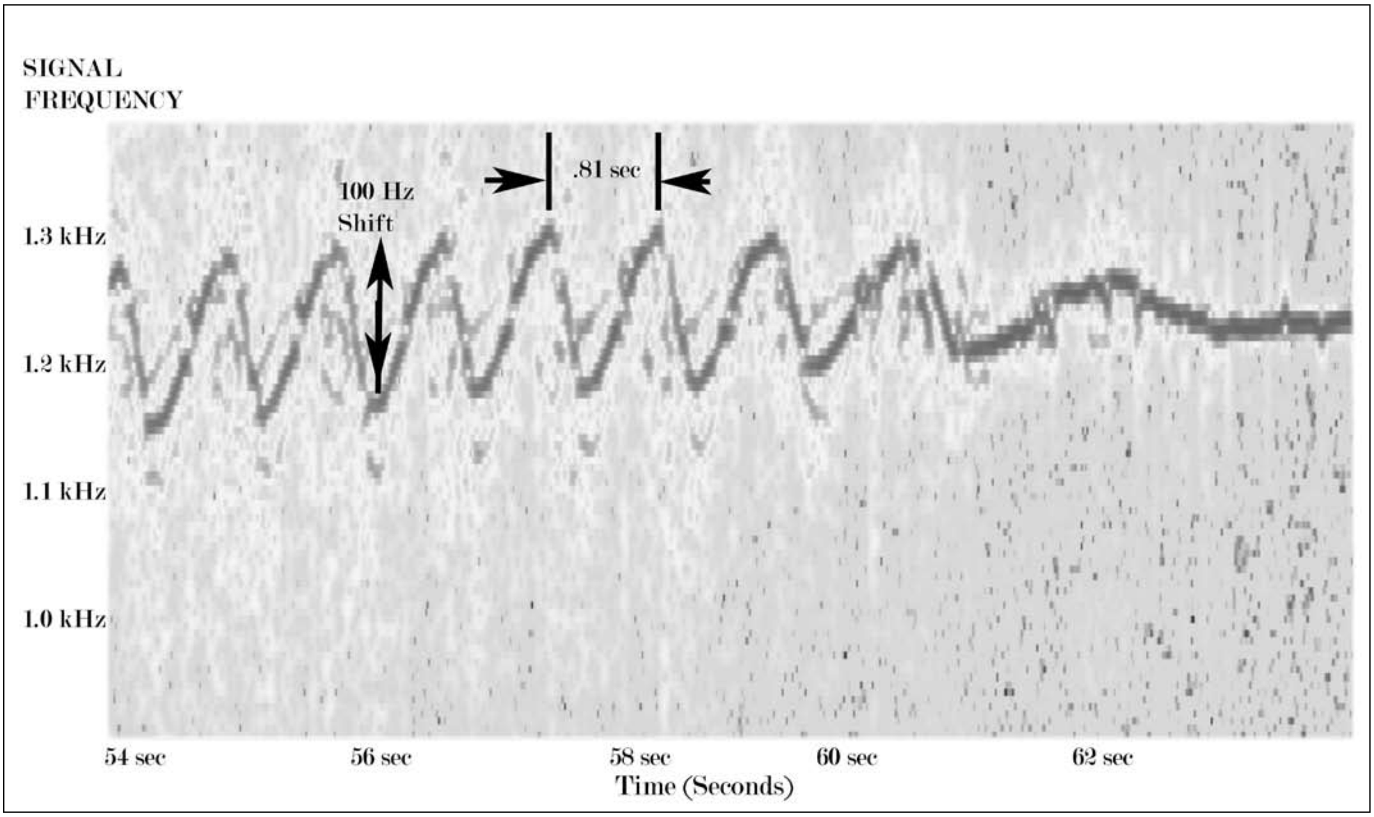


Figure 4 — This spectrogram shows the data for the example of Figure 3. You can measure the rotation period of 0.81 s over most of the waveform, with a peak to peak Doppler shift near 100 Hz. This corresponds to a velocity of 11 m/s.

4) Start the Spectrogram software and you will see it displaying a horizontal line at the frequency of the tuned tone. There may be some drift to this line if the transmitter is drifting.

The analysis of the data requires establishing a reference line, that is, a frequency when the object being measured is standing still. This frequency is arbitrary and just needs to be in the audio pass-band of both the receiver as well as the computer sound card. What we are interested in is the frequency changes from this reference value. For example, the baseline value in Figure 7 was 1382 Hz. Everything is referenced to this baseline value. The peak frequency is 1703 Hz. The difference between peak and baseline is 321 Hz. The conversion to velocity is done using Equation 1, $f_{rec} = f\,(1+v/c)$, which can be simplified to

$$v = c \times \Delta f / f \qquad \text{[Eq 2]}$$

for small Doppler shifts in comparison to the radio frequency. For a 1260 MHz RF signal:

$$v = \Delta f \times 0.238 \text{ m/s} \qquad \text{[Eq 3]}$$

Applications

As previously mentioned, my original motivation came from tracking rockets but my first proof of principle experiment involved putting the transmitter at the end of a 5 foot long string and swinging the transmitter in a circular pattern above my head, much like a cowboy about to rope a steer. For this test, the receiver is located several feet outside and away from the circular trajectory of the transmitter. In fact, the receiver can be located as far away from the transmitter as signal levels will permit and the same spectrogram will result. Figure 3 shows this arrangement. Swinging the transmitter in a circle results in a Doppler frequency increase as the transmitter moves toward the receiver and then a Doppler frequency decrease as the transmitter moves away from the receiver. This produces a roughly sinusoidal pattern, which repeats for every circle the transmitter traces out. The faster you swing the transmitter, the greater the Doppler shift.

The data I collected in this experiment is shown in Figure 4. It is possible to interpret the rotation period as 0.81 s, the frequency shift as 100 Hz, or about 50 Hz positive as the transmitter moves toward the receiver and 50 Hz negative as the transmitter moves away from the receiver. Finally, the velocity from the Doppler data is about 11 m/s. For a 5 ft (1.5 m) rope and a 0.84 s period, we can verify by calculation that the frequency shift is ±50 Hz. The same effect could also be achieved with the transmitter at a fixed location and swinging the antenna. The antenna is located at the end of a coaxial cable tether. In fact, the latter is the basis of a popular direction finding (DF) antenna, but in the DF Doppler antenna, rotation is accomplished using electronic switching rather than mechanical motion as was done here.[5]

A second application I tried was to have the receiver and receive antenna at a fixed location on the side of a road and to mount the transmitter inside a vehicle as shown in Figure1. I then drove the vehicle, initially located several hundred feet from the receiver, at a constant velocity, say 60 mph, toward the receiver and continued on at this constant velocity several hundred feet down the road past the receiver. When the vehicle is at zero velocity there is no frequency shift. Upon accelerating to 60 mph, however, and then remaining at this velocity there is a positive frequency shift (from the zero velocity frequency). As the vehicle passes the receiver, the received signal makes an abrupt drop in frequency to a new frequency that is negative (below the zero velocity frequency) because now the vehicle has passed the receiver and is moving away from it. Figure 5 shows the spectrogram for this data. The velocity doesn't have to be constant and

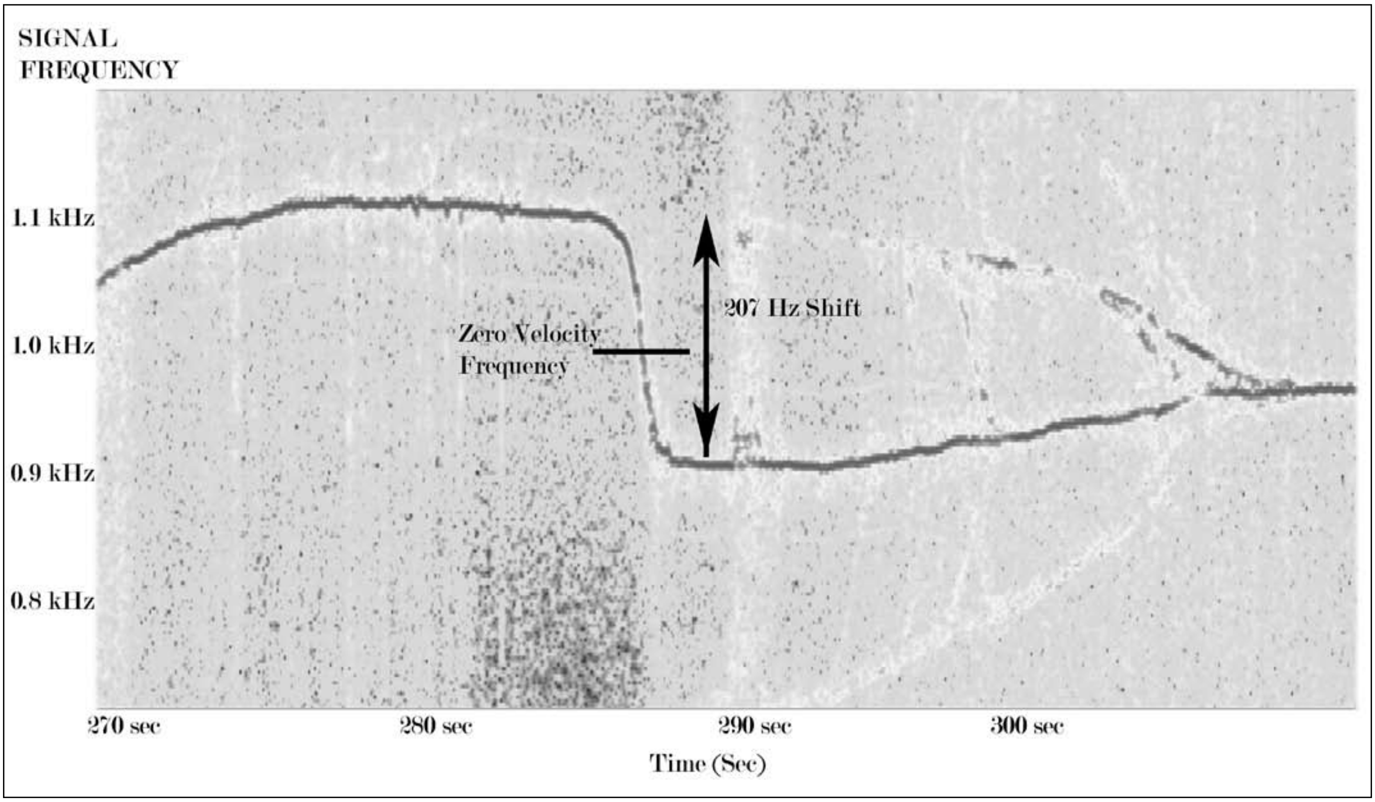


Figure 5 — This spectrogram shows data for the moving car experiment. The transmitter is in car moving past the receiver at near constant velocity after an initial acceleration. The abrupt frequency change is 207 Hz. The velocity of the car is 24 m/s (55 mph). The frequency change is twice the Doppler shift, since it goes from positive to negative as the car passes the receiver. You can also see a region of deceleration as the car slows down after passing the receiver.

definitely is not during the acceleration and braking portions. The spectrogram provides a direct readout of the velocity profile. This might be useful for telling how long it takes to brake a vehicle as well as how fast a vehicle might go from 0 to 60 mph.

The third application is model rocketry tracking, which most definitely uses a variable velocity profile. From this profile such things as fuel burnout time, peak velocity, altitude and time to the ejection charge can be directly observed. Since I began this work several years back and in the intervening years a number of manufacturers have come up with on-board data recorders that use MEMS sensors to measure both acceleration and atmospheric pressure to come up with these same parameters. Although these on board measurement units work fine, they are more complex than a simple transmitter, and also do not have real-time readout. Some of them do have additional telemetry transmitters. Again my goal was to keep the on-board electronics portion simple and inexpensive.

In rocketry, the Doppler frequency shift is always downward upon liftoff. This of course assumes the rocket is moving away from the receiver as shown in Figure 6. If it isn't, that is a completely different problem since I normally locate the receive antenna near the launch pad. If the ejection charge occurs at or before apogee, the frequency shift will be negative through the entire flight. In general there isn't enough resolution to measure the positive velocity seen as the rocket slowly descends back under a parachute. Of course if the rocket comes in ballistic, that would easily be visible on the spectrogram.

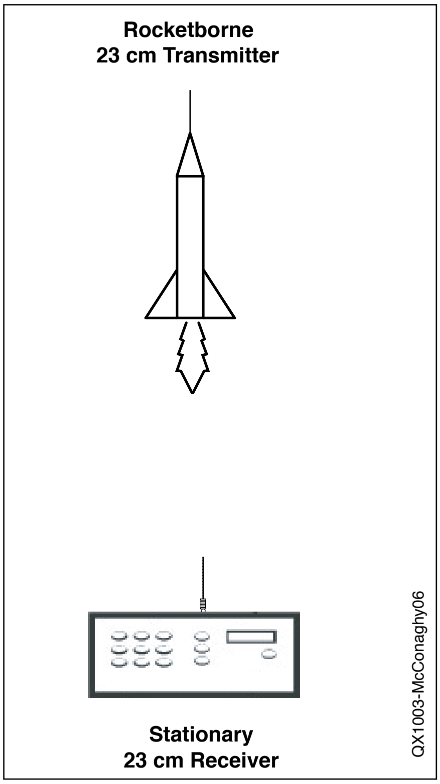


Figure 6 — Here is a drawing that shows the model rocketry application. The transmitter in the rocket is moving away from the receiver, which is on the ground.

Some of the data I took showed a positive frequency shift upon launch but that was only from accidentally using the LSB (lower sideband) selection on the receiver rather than the USB (upper sideband) selection. The LSB selection causes a frequency inversion of the data.

Figure 7 shows the spectrogram for a single stage rocket. The maximum frequency change is 321 Hz, which corresponds to the peak velocity of 76.4 m/s (171 mph). From the peak velocity, which occurs just as the engine burns out, there is a gradual decrease in velocity to a 74 Hz frequency change which corresponds to 17.6 m/s (39 mph). At this point an ejection charge goes off slowing the rocket to near zero frequency shift. The ejection occurred fairly close to apogee, as the rocket was approaching zero velocity.

The spectrogram for a two stage rocket is shown in Figure 8. From this spectrogram, we can determine that the first stage burned for 1.5 s with a Doppler shift of 119 Hz, corresponding to a speed of 28.3 m/s (63.4 mph)

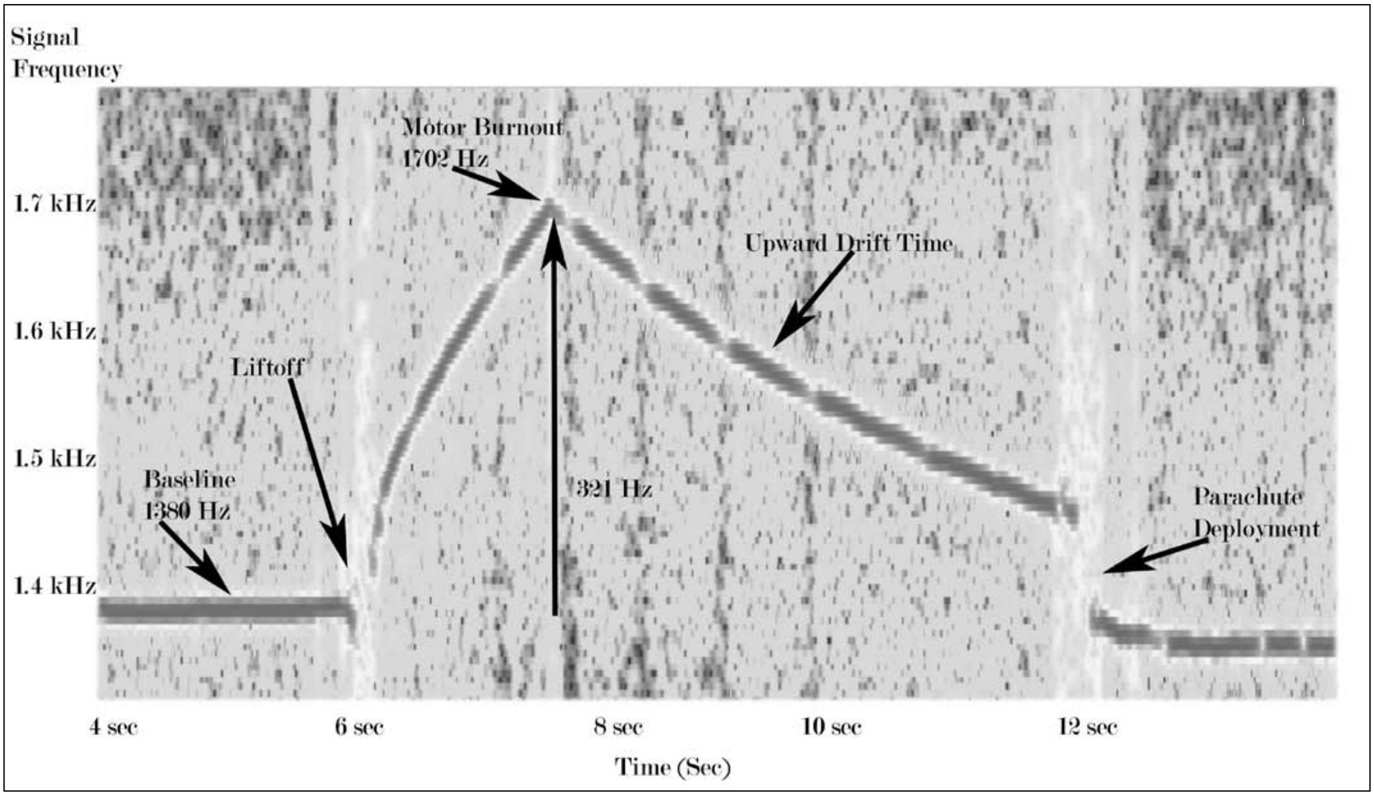


Figure 7 — Here is a spectrogram showing the data a for single stage rocket. The transmitter is on a rocket. The maximum frequency change is 321 Hz and corresponds to a peak velocity of 76.4 m/s (171 mph), at which point the engine shuts down and the velocity slows down to 17.6 m/s (39 mph) as indicated by only a 74 Hz Doppler shift. At 5.6 s after launch the ejection charge fires slowing the velocity back to the baseline. When the rocket is dropping safely under a parachute, there will be little Doppler shift.

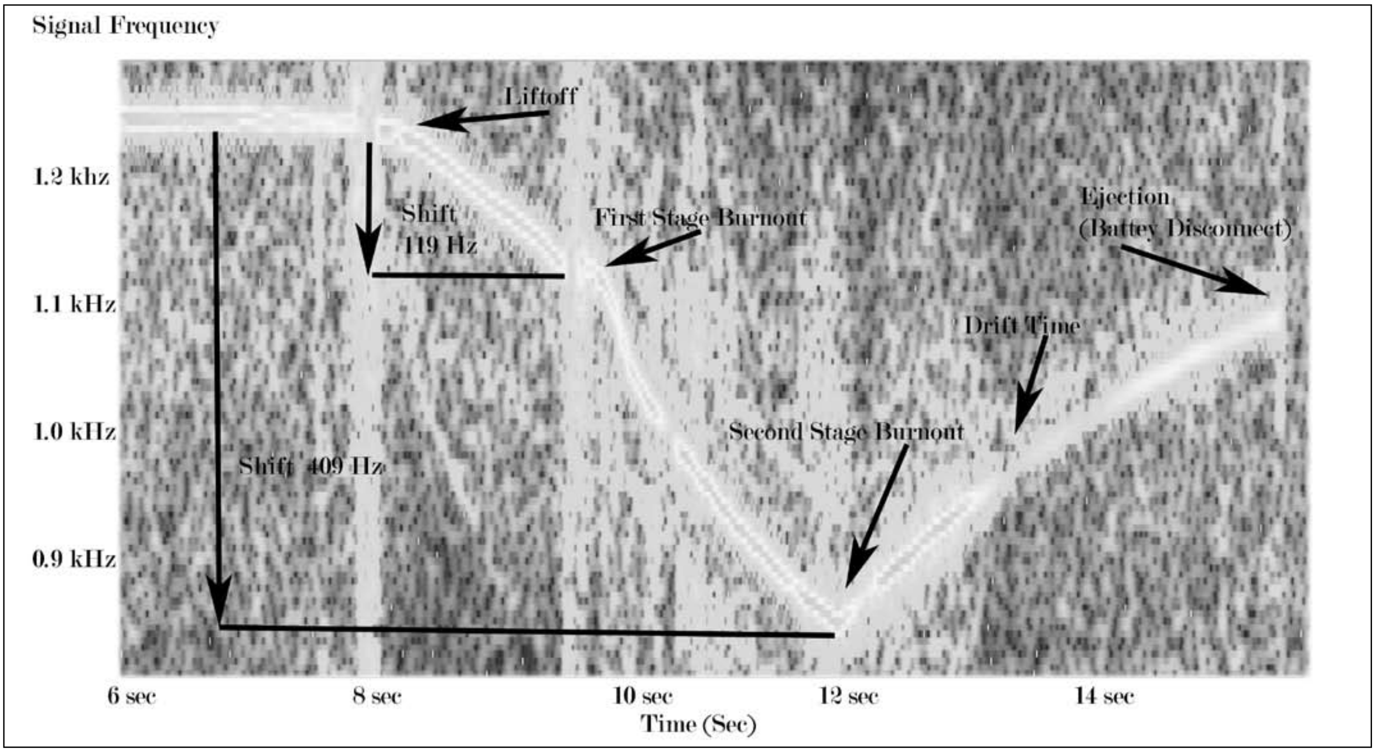


Figure 8 — This spectrogram shows the data for a two stage rocket. The transmitter is on a two stage rocket. The first stage burns for 1.5 s and at this point the Doppler shift is 119 Hz or 28.3 m/s (63.4 mph). The second stage burns for an additional 2.5 s, at which point the Doppler shift is 409 Hz or 97.3 m/s (218 mph) at this point all the fuel is burned and a slow down occurs for an additional 3.4 s, at which time the Doppler shift is 160 Hz or 38 m/s (85.2 mph) . At this point the ejection charge fired but shook the battery connection disabling the RF transmitter

at the end of first stage burnout. Further, the spectrogram shows the second stage burned for an additional 2.5 s with a Doppler shift of 409 Hz, which corresponds to a speed of 97.3 m/s (218 mph) before the second stage fuel was fully burned. After that, a gradual decrease in speed is observed for an additional 3.4 s, at which time the ejection charge fired but shook the battery connection, disabling the RF transmitter. Just prior to the ejection, the rocket was still traveling upward at a speed of 38 m/s (85.2 mph) as evidenced by the Doppler shift of 160 Hz.

Further analysis of the velocity curves can produce altitude data, or more generally, distance data. This is accomplished by integrating the data shown in Figures 7 and 8 with a simple Microsoft *Excel* spreadsheet. The altitude plots are shown in Figures 9 and 10. A peak altitude of 250 m (820 ft) is achieved by the single stage flight and a peak altitude of 370 m (1213 ft) is achieved by the two stage flight.

Summary

The Doppler effect can be used by hams to make speed measurements of cars, swinging transmitters, rockets and other moving platforms. By separating the transmitter and receiver, using readily available computers and software, these measurements can be performed by hams with off-the-shelf radios and lower power levels. It is a lot less complex than you might normally expect for a "Doppler radar" system.

Acknowledgements

I would like to thank both Asher Blum and Rick Schnetz, WA6RAI, for taking time to read this article and for making suggestions to clarify the content.

Chuck McConaghy, WA6SYE, has been a ham since 1971, when he was originally licensed as WN9IBX. He currently holds an Advanced class license. Over the years, Chuck's Amateur Radio activities have included UHF repeater construction, ATV, amateur satellites

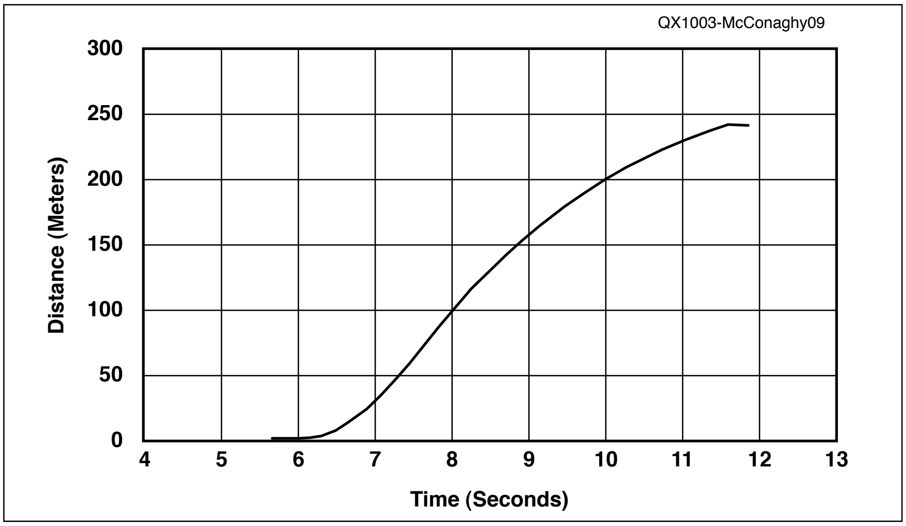


Figure 9 — This data is produced by integrating Figure 7. It shows that a peak altitude of just near 250 meters (820 ft) occurs at the 12 s point. (The launch began at the 6 s point)

and PSK31. He retired in 2007 after 35 years at Lawrence Livermore National Laboratory, where he worked on everything from high speed X-ray diagnostics, integrated optics, ASIC design and MEMS sensors. He holds a BSEE degree from Purdue University and an MSEE degree from Stanford University.

Notes

[1] For more information about the Doppler effect, see: **//en.wikipedia.org/wiki/Doppler_effect**.

[2] There is more information about the DARTS project at **www.hamhud.net/darts**.

[3] For information about the *RockSim* software and other model rocketry information and supplies, see: **www.apogeerockets.com**

[4] You can obtain more information and download a 10-day trial version of the *Spectrogram* software at the Visualizations Software Web site at: **www.visualizationsoftware.com/gram.html** (At press time this Web site was listed as "Under Construction." You can also download an older version (5.17) of the *Spectrogram* software free at: **www.dxzone.com/cgi-bin/dir/jump2.cgi?ID=2056**.

[5] Terrence Rogers WA4BVY, "A DoppleScAnt," *QST*, May 1978, pp 24-28.

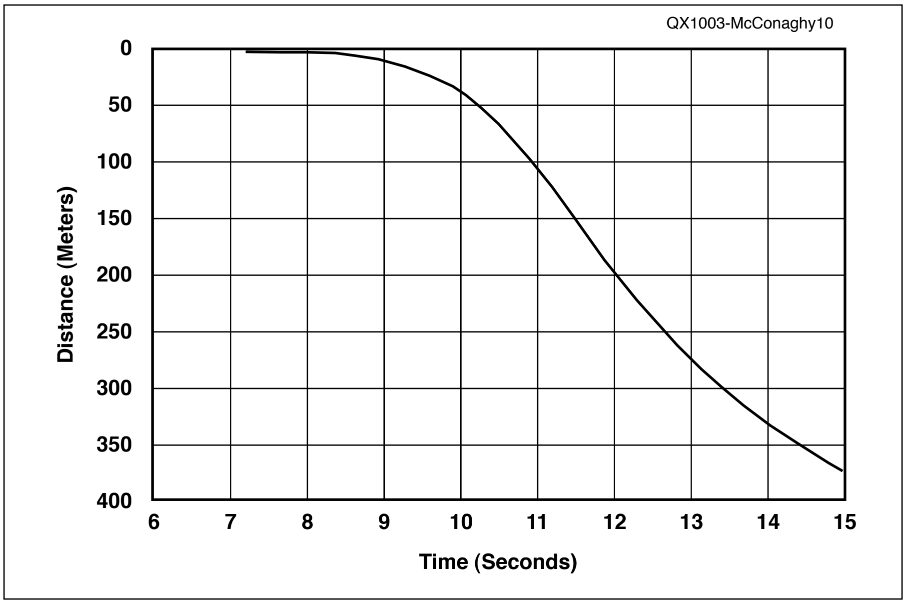


Figure 10 — This data is produced by integrating Figure 8. It shows that a peak altitude of just near 370 meters (1200 ft) occurs at the 15 s point. (The launch began at the 8 s point)